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# The Effects Of Temperature Control On Biological Wastewater Treatment Processes

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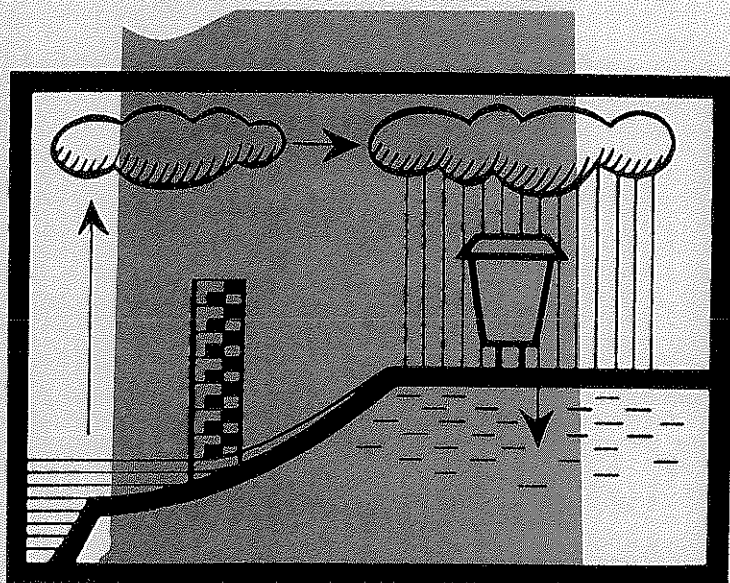
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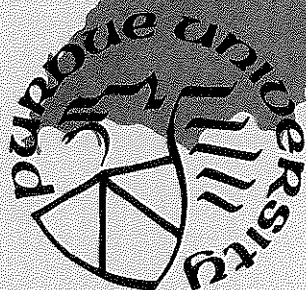
# THE EFFECTS OF TEMPERATURE CONTROL ON BIOLOGICAL WASTEWATER TREATMENT PROCESSES



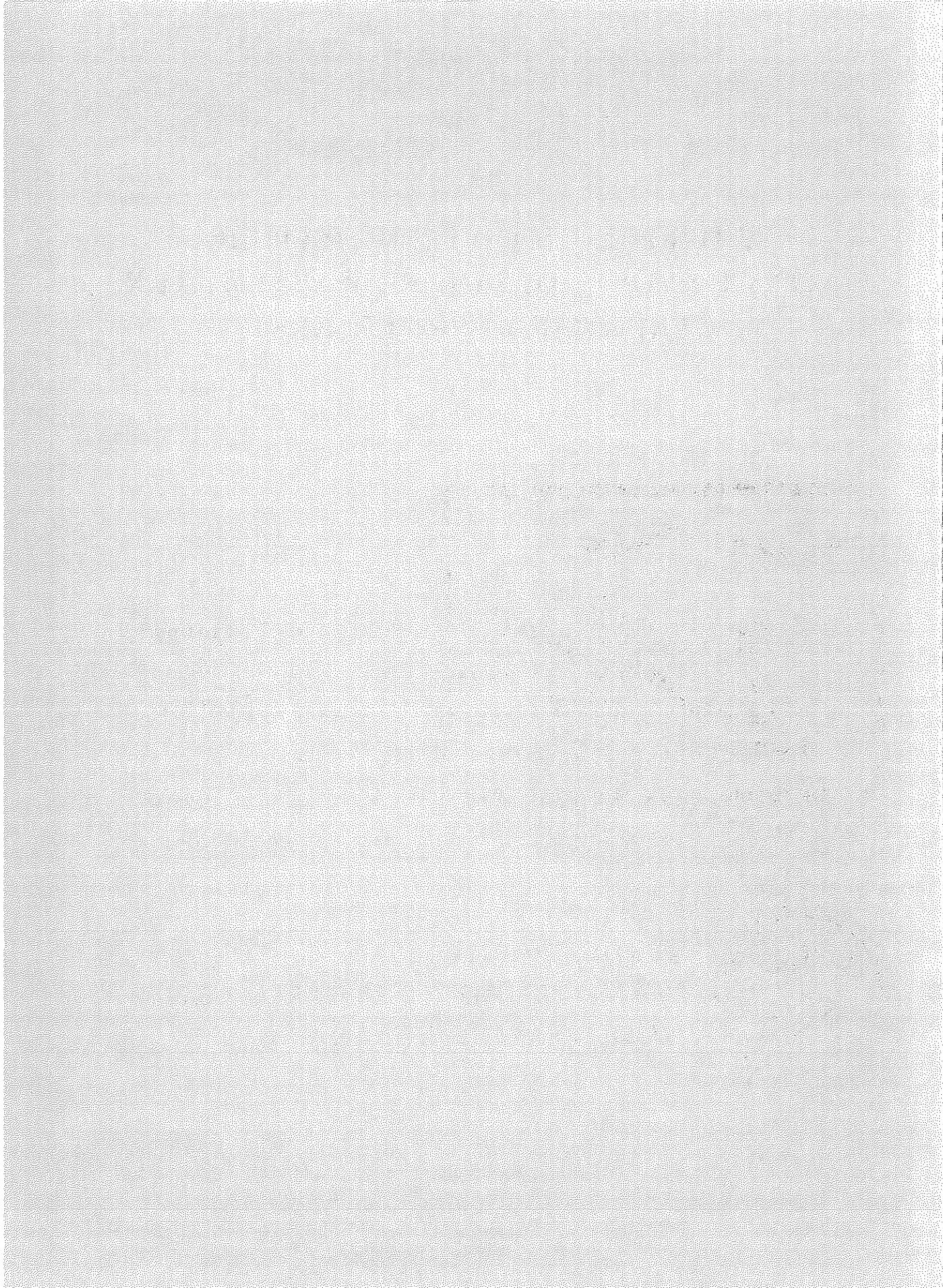
by

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March 1978



PURDUE UNIVERSITY  
WATER RESOURCES RESEARCH CENTER  
WEST LAFAYETTE, INDIANA



THE EFFECTS OF TEMPERATURE  
CONTROL ON BIOLOGICAL WASTEWATER  
TREATMENT PROCESSES

by

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and

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## FOREWORD

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## NOMENCLATURE

Symbol	Definition	Units
$a$	constant in pressure equation	$K^{-1}$
$A$	settler area	$ft^2$
$A_1$	constant in Arrhenius expression	$hr^{-1}$
$b$	specific decay rate constant of biomass	$hr^{-1}$
$b_o$	constant in pressure equation	$K$
$b_1$	specific decay rate constant of viable cells	$hr^{-1}$
$b_2$	specific decay rate constant of non-viable cells	$hr^{-1}$
$c$	actual concentration of oxygen in water	$mg/l$
$c_i$	suspended solids concentration of a layer within the settling tank	$mg/l$
$c_L$	suspended solids concentration of a layer within the settling tank with minimum capacity for transmitting solids	$mg/l$
$c_m$	minimum value of suspended solids concentration in settler feed	$mg/l$
$c_u$	maximum underflow concentration attainable without loss of solids to the effluent	$mg/l$
$c^*$	saturation concentration of oxygen in water	$mg/l$
$c_m^*$	mean saturation concentration of oxygen in water	$mg/l$
$c_p$	specific heat of water	$J/kg-C$
$D_p$	diameter of particle in Stokes law settling velocity equation	$m$
$F$	influent plant flow rate	$gal/day$



$F_r$	recycle flow rate	gal/day
$F_w$	wastage flow rate	gal/day
$g$	acceleration of gravity	m/sec <sup>2</sup>
$G$	applied flux to settler	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$G_a$	applied downward solids flux	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$G_{ec}$	upward solids flux from clarifier model	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$G_{et}$	upward solids flux due to thickener failure	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$G_g$	subsidence flux through settler	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$G_L$	limiting solids handling capacity of settler	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$G_T$	total downward flux through settler	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$G_u$	bulk flux through settler	$\frac{\text{mg/l-gal}}{\text{ft}^2\text{-day}}$
$k_o$	reaction velocity	hr <sup>-1</sup>
$K$	constant in Keinath equation	-
$K_s$	Monod saturation constant	mg/l
$K_L a$	volumetric mass transfer coefficient	hr <sup>-1</sup>
$K^*$	system constant	-
$m_a$	exponent in Eckenfelder equation	-
$n$	exponent in Eckenfelder equation	-
$N'$	rate of oxygen transfer	mg/hr
$O_t$	percent of oxygen in air leaving aeration tank	-

P	power required for aeration	HP
$P_a$	atmospheric pressure	psi
$P_c$	absolute pressure of compression	psi
$P_x$	rate at which biosystem is producing cells	lb/day
$P'$	absolute pressure at depth of air release	psi
q	air flow rate from one sparger	ft <sup>3</sup> /min
Q	total air flow rate	ft <sup>3</sup> /min
R	universal gas constant	cal/g <sub>mole</sub> -K
$r_{dx}$	rate of decay of the biomass	mg/l-hr
$r_{dx_v}$	rate of decay of viable cells	mg/l-hr
$r_{Dx_v}$	rate of production of dead cells from viable cells	mg/l-hr
$r_{Gx_v}$	rate of growth of viable celss	mg/l-hr
$r_{O_2}$	rate of oxygen demand by biomass	mg/l-hr
$r_s$	rate of substrate utilization	mg/l-hr
$r_x$	net production rate of biomass	mg/l-hr
$r_{x_d}$	net production rate of dead cells	mg/l-hr
$r_{x_v}$	net production rate of viable cells	mg/l-hr
S	effluent soluble substrate concentration	mg/l
$S_D$	concentration of dissolved solids	g/l
$S_e$	total effluent quality	mg/l
$S_o$	influent soluble substrate concentration	mg/l
T	temperature	C, K
$\bar{t}$	hydraulic residence time (V/F)	hr

$u$	average bulk downward velocity in thickener due to sludge withdrawal	gal/ft <sup>2</sup> -day
$u_o$	temperature characteristic	cal/mole
$u_p$	settling velocity of a particle which settles according to Stoke's law	m/s
$V$	volume of aeration tank	gal
$V_i$	settling velocity of sludge at concentration $c_i$	gal/ft <sup>2</sup> -day
$X$	suspended solids concentration in aeration tank	mg/l
$X_a$	apparent solids concentration to thickener model	mg/l
$X_d$	nonviable suspended solids concentration in aeration tank	mg/l
$X_{dr}$	nonviable suspended solids concentration in recycle flow	mg/l
$X_e$	effluent suspended solids concentration	mg/l
$X_{ec}$	portion of $X_e$ due to imperfect clarification	mg/l
$X_{et}$	portion of $X_e$ due to thickener failure	mg/l
$X_r$	biomass concentration in recycle flow	mg/l
$X_u$	suspended solids concentration in settler underflow	mg/l
$X_v$	viable suspended solids concentration in aeration tank	mg/l
$X_{ve}$	viable suspended solids concentration in effluent flow	mg/l
$X_{vr}$	viable suspended solids in recycle flow	mg/l
$X_w$	biomass concentration in wastage flow	mg/l
$Y_g$	true growth yield coefficient	mg cells/ mg substrate
$z$	depth of air release	ft

$\alpha$	recycle flow rate as a function of influent flow rate ( $\alpha = Fr/F$ )	-
$\beta$	oxygen equivalent of cells formed	mgO <sub>2</sub> /mg cells
$\beta_o$	exponent in Keinath settling velocity equation	-
$\gamma$	specific death rate constant of dead cells	hr <sup>-1</sup>
$\theta$	temperature constant in Keinath equation	
$\theta_c$	sludge age	days
$\theta_K$	temperature constant for variation of $K_L a$ with temperature	-
$\mu$	gross specific growth rate	hr <sup>-1</sup>
$\mu_f$	fluid viscosity	kg/s-m
$\mu_m$	maximum specific growth rate	hr <sup>-1</sup>
$\nu$	kinematic viscosity	m <sup>2</sup> /s
$\rho$	density of water	kg/m <sup>3</sup>
$\rho_f$	density of fluid	kg/m <sup>3</sup>
$\rho_p$	density of particle	kg/m <sup>3</sup>

## ABSTRACT

This study is specifically concerned with the feasibility of using waste heat to optimize the performance of a biological wastewater treatment facility through temperature control. The effect of temperature on biological wastewater treatment was modelled by considering its influence on several important processes. In particular, the specific influence of temperature on the bacterial kinetic parameters, the oxygen transfer process and the biomass settling was included in the model. The parameters chosen to determine the effect of temperature on the system were effluent quality, mass wastage (sludge disposal) rate, and the power requirements for aeration. These parameters reflect both the primary purpose of waste treatment and the major operating costs. The parameters were determined as a function of both temperature and sludge age, since both of these variables may be used to control the operation of a wastewater treatment facility.

The results of a computer simulation show that an optimal temperature for operation of a secondary wastewater treatment facility is approximately 25 C. Operation at this temperature provides improved effluent quality and reduced sludge production, without incurring an excessive increase in the power requirements for aeration.



## CHAPTER 1. INTRODUCTION

### 1.1 General Remarks

Events of the past few years have suggested that it will become increasingly more difficult to satisfy future energy needs. Increases in global population and per capita energy consumption, combined with fossil fuel depletion, are causing greater demands to be placed on diminishing energy resources. This condition has stimulated activities in two general directions, which include the development of alternative energy sources and the implementation of energy conservation.

Energy conservation measures may assume several forms, which include the elimination of unnecessary consumption, the improvement of energy conversion efficiencies, and the use of energy rejected in thermal energy conversion processes. The last alternative involves the use of heat recovery systems to derive benefits from energy which would otherwise be rejected to the environment. The greatest opportunities for waste heat utilization are in the fields of industrial processing and in electrical power production.

This study is concerned with utilization of the waste heat from electrical power generation. Waste heat from a power cycle is a natural consequence of the second law of



thermodynamics, which imposes limits on the amount of work which can be obtained from heat. In the typical power plant, which uses condensing cycle steam turbo-generators, more than 60% of the input energy is rejected as low grade waste heat. This heat is discharged through the condenser cooling water and is ultimately rejected to the atmosphere via a cooling pond or tower.

Although the temperatures associated with the condenser discharge are only slightly above ambient (generally in the range from 25 to 45 C), the cooling water flow rate is large (approximately  $0.05 \text{ m}^3/\text{s}$  per MWe) and the amount of heat rejected is substantial. Because of the comparatively low temperatures associated with this rejected heat, however, there are few ways in which it may be used. It is, for example, impractical to use it as an energy source for the extraction of useful work. The only way in which the heat may, in fact, be used is to sustain useful biological processes at, or near, their optimum temperatures. Since the rate of most biological conversion and growth processes is maximized at temperatures which may vary from 25 to approximately 40 C, power plant waste heat is well suited for maintaining temperatures in the desired range. Applications which have been considered include the use of waste heat to maintain optimum growth conditions in aquacultures of fish and shrimp, in mass algal cultures and in greenhouse complexes (1). However, one such application which has

received very little consideration involves the use of waste heat to maintain optimum microbial growth conditions in biological wastewater treatment systems.

### 1.2 Waste Heat Utilization for Wastewater Treatment

Because of the large volumetric flows which must be handled, little consideration has heretofore been given to maintaining temperature control over biological wastewater treatment processes. Since such processes currently operate at ambient conditions, the rates at which they occur are subject to diurnal and seasonal variations. Although summer temperatures are conducive to high microbial growth rates, these growth rates are severely retarded during winter in the temperate latitudes. The seasonal variation in the average temperature of an aeration tank in Indianapolis, Indiana is shown in Table 1.1. From the results, it is evident that the variation of temperature is appreciable, and when considered with the results of Figure 1.1, it is obvious that a significant reduction in the rate of waste treatment occurs from late autumn to early spring. Moreover, the results provide some incentive for considering the benefits to be derived from maintaining control over the system temperature.

Additional incentive is provided by the Federal Water Pollution Control Acts Amendment of 1972, which commits the nation to an intensive effort to clean and preserve its water resources. By July 1, 1977 all municipalities must have secondary wastewater treatment systems, which use the best

Table 1.1 Average temperature in the aeration tank of the Indianapolis, Indiana sewage treatment plant for the years 1935-1939 (2).

<u>Month</u>	<u>Temperature of Aeration Tank, (C)</u>
January	14.51
February	14.10
March	14.72
April	15.79
May	18.71
June	21.48
July	24.01
August	25.43
September	24.23
October	21.87
November	19.04
December	16.59

practicable technology. Effluent limitations are 30 mg/l BOD average, and a maximum weekly average of 45 mg/l (4). By 1983, waste treatment systems must be using the best available technology, with a goal of achieving zero discharge of pollutants by 1985 (5). In this regard it is possible that heat may be applied to increase removal efficiencies and thereby to aid in meeting effluent standards.

Currently, wastewater treatment plant designers must design for the worst possible case, which is during the winter when biological activity slows. This necessitates larger volumes than are necessary during the summer, when biological

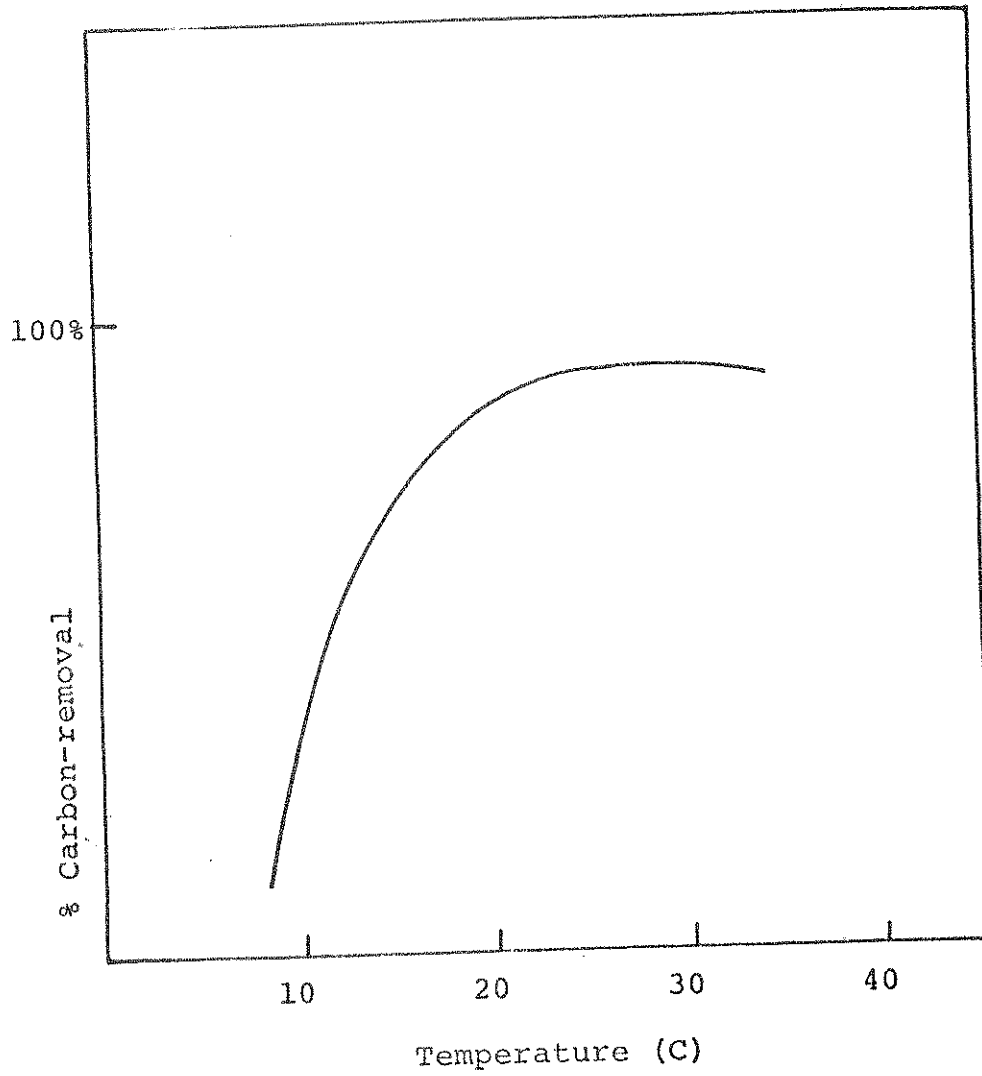


Figure 1.1 Temperature dependence of efficiency of biological processes for an activated sludge system (27).

activity is increased, and adds to the cost of the system. The present study therefore considers the advantages which may be derived by siting an electrical power plant and a wastewater treatment plant adjacent to each other (Figure 1.2). Assuming an electrical energy consumption of 8700 kw-hr/year for a typical residential unit (6), the average instantaneous load per residential unit will be approximately 1 kWe and a power plant output of 1 MWe would be needed to satisfy a community of 1000 residential units. Waste heat from the power plant could be dissipated in a cooling pond with a surface area of approximately 2 acres<sup>+</sup>, as well as in a secondary waste treatment system. The waste treatment system could be made an integral part of the cooling pond or installed adjacent to the pond, as shown in Figure 1.2. Warm water from the powerplant could be used to control temperature in the aeration and settling tanks and subsequently be rerouted to the cooling pond. The wastewater discharged from a residential unit is approximately 300 gal/day ( $1.3 \times 10^{-5} \text{ m}^3/\text{s}$ ) (8), in which case the entire community will be discharging  $0.013 \text{ m}^3/\text{s}$ .

Using a hydraulic residence time of 5 hours and an overflow rate of  $3.30 \times 10^{-4} \text{ m/s}$  the volume of the aeration tank is  $250 \text{ m}^3$ , and the settling tank will have a surface

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<sup>+</sup>Actual surface area requirements may range from 0.75 to 4 acres per MWe, depending upon local meteorological conditions (7).

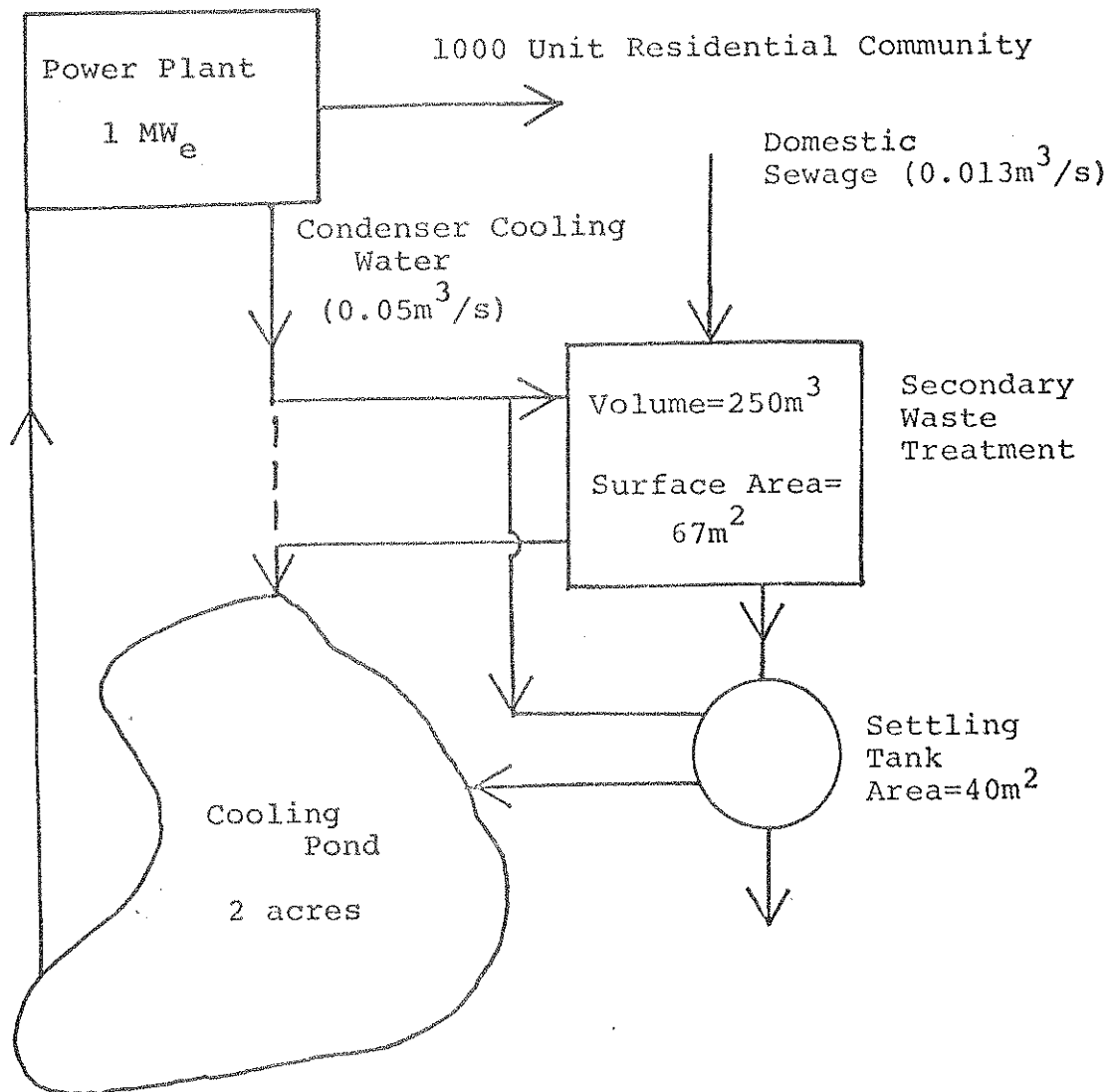


Figure 1.2 Integrated electrical power plant and wastewater treatment system for a community of 1000 residential units

area of  $40 \text{ m}^2$ . These values were determined using the procedure outlined in Chapter 2 and will provide a good quality effluent from typical domestic sewage for a sludge age greater than 3 days. This provides an idea of the relative magnitudes of the size and flow rate of power plant cooling water systems and waste treatment facilities.

The purpose of this study is to consider the performance of a biological waste treatment system, for which temperature control may be maintained. In particular, system performance will be determined as a function of temperature for a Completely Mixed Activated Sludge (CMAS) system. The next section provides a description of the system and the assumptions necessary for analysis.

### 1.3 The Completely Mixed Activated Sludge System (CMAS)

Although the idea originated in 1919, implementation of the completely mixed activated sludge system is relatively new, having first been used for full-scale wastewater treatment in the late 1950's (9). The system provides an efficient means for removing non-settlable, finely divided colloidal particles and dissolved organic material from a wastewater stream (10).

A CMAS may be regarded as a modification of a once-through biological treatment process. In the once through process, the wastes enter an aeration tank in which the biological mass removes the dissolved organic material. The



treated wastewater and the micro-organisms which have been generated are then extracted from the aeration tank for further treatment. This process introduces several problems, however, foremost of which is the relatively long residence time<sup>+</sup> required to remove the dissolved organic material. The quality of the effluent increases with increasing residence time, and for the once-through system, large residence times (hence large aeration tank volumes) are needed to achieve satisfactory effluent quality. The system allows little opportunity for operator control and responds poorly to shock loads associated with abrupt changes in operating conditions (such as influent dissolved organic matter or temperature).

The CMAS overcomes the problem of limited control by a very simple modification. In effect it provides for separation of a portion of the cells from the waste in a settling tank with subsequent recycling of the cells to the aeration tank. This provides for considerable flexibility in operating the system. Moreover this flexibility may be obtained without diminishing the quality of the effluent. The operation is no longer dependent on the hydraulic residence time of the system, but on the mean cell residence time, or sludge age, which is the total microbial mass in the system divided by the total microbial mass withdrawn from the system per

---

<sup>+</sup>The residence time is simply the volume of the aeration tank divided by the wastewater volumetric flow rate.

unit time,

$$\theta_c = \frac{VX}{F_w X_w + (F - F_w) X_e} \quad (1.1)$$

where  $\theta_c$  is the mean cell residence time, days;  $X$  is the cell concentration in the aeration tank, mg/l;  $V$  is the volume of the aeration tank, gal;  $F$  is the volumetric flow rate into the aeration tank, gal/day;  $F_w$  is the wastage flow rate from the settling tank, gal/day;  $X_w$  is the concentration of cells in the wastage flow, mg/l; and  $X_e$  is the concentration of cells in the effluent flow, mg/l.

A schematic of the system is shown in Figure 1.3. The diagram depicts a reactor of volume  $V$ , receiving a wastewater flowrate  $F$ , with a dissolved organic concentration  $S_o$ . The dissolved organic matter is a soluble substrate, off which the bacterial mass feeds. The concentrations of soluble substrate in the wastage flow,  $F_w$ , the recycle flow,  $F_r$ , and the effluent flow are assumed to be equivalent to the soluble substrate concentration in the aeration tank. The microbial cell concentrations are  $X$  for the aeration tank,  $X_e$  for the effluent,  $X_w$  for the wastage flow, and  $X_r$  for the recycle flow. In the CMAS, the recycle flow is proportional to the influent flow

$$F_r = \alpha F \quad (1.2)$$

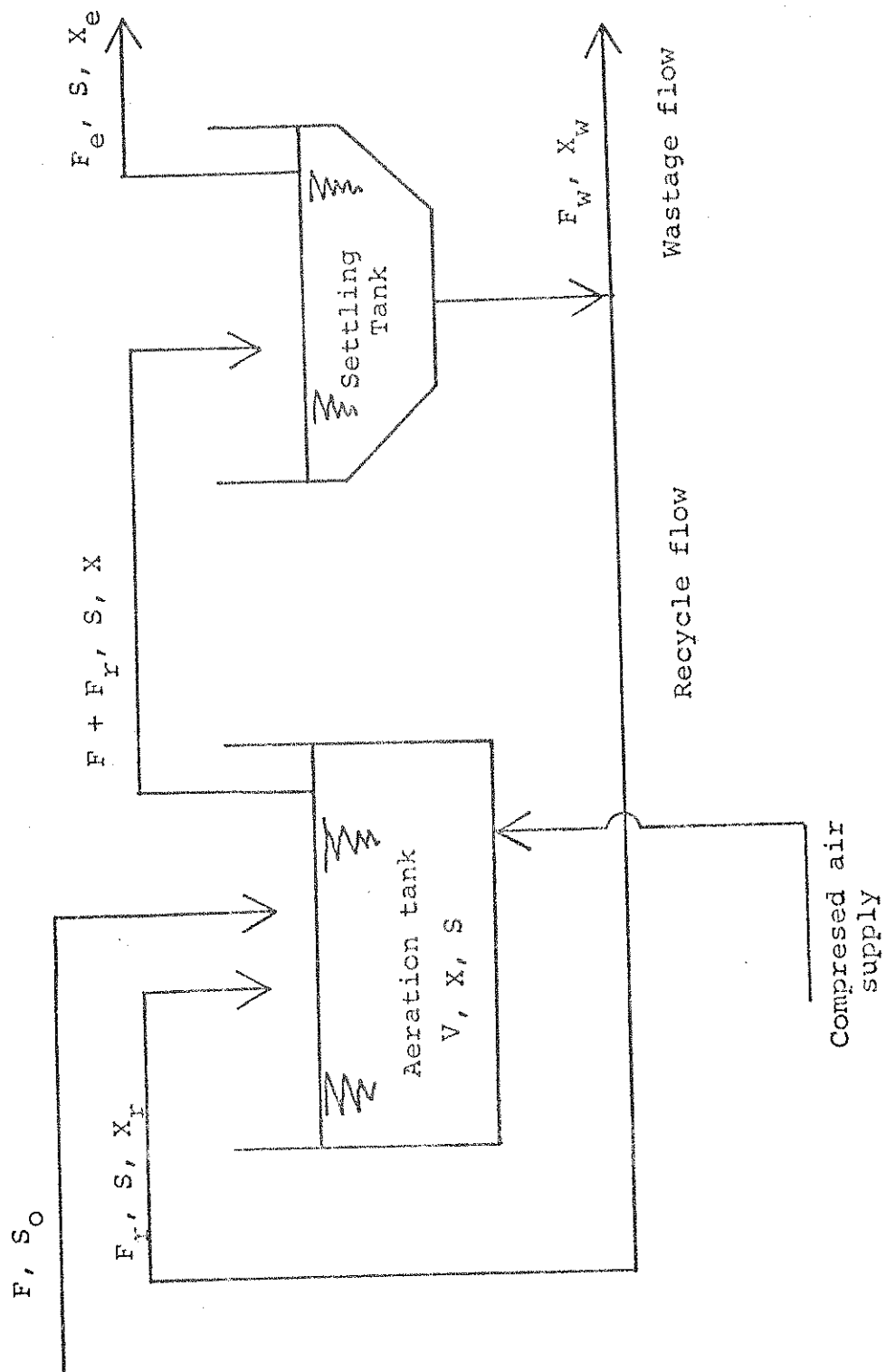


Figure 1.3 Completely mixed activated sludge system.

where  $\alpha$  is termed the recycle ratio (the fraction of the influent flow that is recycled). In the system the aeration tank will be approximated as a continuously stirred tank reactor, in which case its composition is uniform throughout and the concentration of cells in the aeration tank is equal to the cell concentration for the flow leaving the tank.

Wastewater from the aeration tank flows to a settling tank in which the suspended solids (that is, the bacterial cells) settle to the bottom. Hence the concentration of cells in the effluent flow,  $X_e$ , is much less than the concentration of cells in the aeration tank. From the bottom of the settling tank, the solids are removed in one stream, which is split into recycle and wastage flows. The cell concentrations in these flows are equal ( $X_r = X_w$ ) but greater than the cell concentration in the aeration tank. The recycling of cell mass enables the bacteria in the aeration tank to be maintained at a high, nearly constant concentration and is, in fact, one of the major advantages of a CMAS. This aids in protecting the system from sudden shock inputs.

Certain assumptions must be made in order to develop a suitable mathematical model of the system. The first assumption is that the only growth-limiting substrate is the organic waste, in which case ample nitrogen, oxygen and phosphorous are presumed to be present. Hence, the soluble substrate is assumed to govern the growth kinetics of the

microbial culture, and its concentration determines how rapidly cells are formed. It is also assumed that only heterotrophic organisms contribute to the cell mass. In addition, it is assumed that all soluble substrate removal occurs in the aeration tank. This assumption is reasonable due to the low concentrations of substrate in the settler, and the rapid settling of cells, which gives only a small concentration of cells in the bulk of the liquid. These effects combine to produce negligible substrate removal in the settling tank and support the contention that the concentrations of soluble substrate in the effluent, wastage, and recycle flows are equal. It is also assumed that all biological activity ceases in the settler, so that no further cell death or decay may occur. Since cell activity cannot cease immediately, this assumption is open to some question and is currently being investigated (11). The final assumption is that the mass of cells in the aeration tank is greater than the mass of cells in either the wastage or recycle streams. This is reasonable if a suction-type sludge pickup is used to remove the sludge rapidly from the bottom of the settler.

The foregoing discussion delineates the system and the assumptions under which it will be analyzed.

#### 1.4 The Nature of the Problem

The effect of temperature on a CMAS is not easy to predict, because of the complex interactions which are

established by recycling a portion of the waste flow. Temperature affects the growth kinetics of the bacteria, the settling characteristics of the sludge, and the oxygen transfer capabilities of the system. These effects establish a set of interactions in the system which must be coupled to determine the overall system performance. This performance of the system may be measured in terms of the effluent quality, the amount of sludge produced, the oxygen requirements and whether or not the system meets prespecific operating requirements.

#### 1.5 Statement of Objectives

To determine the feasibility of using waste heat from a power plant to enhance wastewater treatment, a model must be developed which accounts for the effect of temperature on the performance of an activated sludge system. Development of such a model requires that the effect of temperature on the characteristics of both the aeration tank and the settling tank be known. Moreover, to determine whether or not temperature control is effective, it is necessary to develop an integrated model of the entire system. In doing so, the temperature dependent parameters must be identified and incorporated in the model. Hence the purpose of this study is to determine the temperature dependent parameters, develop an integrated model of the system, and determine an optimum operating temperature for the system. This model

will be for an existing design, and will seek to determine the best operating temperature for that system, not to optimize a new facility with respect to temperature.

### 1.6 Method of Analysis

Since the proposed study requires knowledge of the effects of temperature on each of the component processes, the initial step involved performing a literature review of the effects of temperature on secondary wastewater treatment systems. Extensive work (2,3,24,26,27,28,36,39, 54,63,64) has been done on individual aspects of the effect of temperature on waste treatment processes, but no consideration of the effects of temperature on the entire system has heretofore been undertaken. The next step involved formulating a mathematical model of the system and solving the relevant equations using a digital computer.

It should be noted that two previous studies have considered the possibility of using waste heat for wastewater treatment (12,13). The first study, that of Humenick, Morgan and Froh (1972) considers a combined system of wastewater and condenser cooling water. That is, the wastewater is used to supply the makeup water of the cooling water supply of the power plant. The study considers two possibilities, that of using the untreated waste from a municipality, or the treated effluent from a secondary waste treatment facility. The study differs from the present effort in that the system considered for waste treatment is a facultative waste



stabilization pond, which is a complex ecosystem of anaerobic and aerobic bacteria and algae. The discussion of such ponds must be highly empirical due to the three separate microbial populations and the necessity of accounting for oxygen transfer from the atmosphere. The study fails to clearly delineate the problems associated with the system. Although it provides a general survey of the flow rates needed to balance wastewater treatment and cooling water makeup requirements, it fails to provide an adequate model of the system, from which performance and possible problem areas could be predicted. However the study does suggest the potential merit of the application and the need for further research.

The second study, that of Agardy, Fields and Staackman (1973) is a survey of the technical and economic feasibility of using waste heat to improve conventional and advanced wastewater treatment processes. Sources of waste heat are identified, and the effects of increased temperature on conventional waste treatment processes such as activated sludge, nitrification and ammonia stripping and on advanced waste treatment processes such as reverse osmosis, activated carbon, ion exchange and phosphate removal are explored. The study provides a general survey of the effect of temperature on such processes but, as regards activated sludge, leaves a great deal of room for further investigation. It discusses the effect of temperature on percent BOD removal

but fails to adequately identify the individual parameters which are affected by temperature. It also fails to model the system to predict temperature effects on overall performance and hence falls short of the objectives of the present study.

## CHAPTER 2. MATHEMATICAL MODEL OF THE COMPLETELY MIXED ACTIVATED SLUDGE SYSTEM

### 2.1 Introductory Remarks

The purpose of this chapter is to develop mathematical expressions for the effect of temperature on the performance of a completely mixed activated sludge system (CMAS). The mathematical model includes a description of conditions in the aeration and settling tanks, with particular attention given to bacterial kinetics and to the supply and consumption of oxygen. Calculations based on the model will be performed to determine the effect of temperature on key performance parameters such as effluent quality, wastage production, oxygen demand and power requirements.

This chapter is divided into four sections, the first of which concerns the effect of temperature on bacterial kinetics and growth. The following sections deal with mathematical models for conditions in the aeration tank, for the system oxygen requirements and transfer, and for conditions in the settling tank.

### 2.2 Bacterial Kinetics

The kinetic model in this study is that proposed by Herbert(14), but modified to include cellular decay, as

advocated by Lawrence and McCarty (15). Assuming an ideal CSTR, three simultaneous processes occur. They include cell growth, cell decay and death, and substrate utilization. Assuming that the biooxidation process occurs solely within the completely mixed aeration tank and that it is the result only of heterotrophic organisms feeding upon the growth limiting substrate, the viability model of Topiwala and Sinclair (16) can be used. The concentration of solids in the aeration tank is composed only of viable cells (organisms actively removing substrate for growth) and dead cells (organisms that cannot grow). Hence

$$X = X_v + X_d \quad (2.1)$$

### 2.2.1 Microbial Cell Growth

A kinetic model for the viable organisms may be developed by assuming that cell growth occurs at a rate which is first order with respect to the concentration of viable cells in the aeration tank. That is,

$$r_{GX_v} = \mu X_v \quad (2.2)$$

where  $r_{GX_v}$  is the rate of growth of viable cells, mg/l-hr,  $\mu$  is the gross specific growth rate,  $\text{hr}^{-1}$ , and  $X_v$  is the viable cell concentration in the aeration tank, mg/l.

The gross specific growth rate  $\mu$  is a function of the concentration of the growth limiting substrate  $S$ . Monod (17) observed that the relation between  $\mu$  and  $S$  may be described by the following hyperbolic equation

$$\mu = \frac{\mu_m(T) S}{K_s(T) + S} \quad (2.3)$$

where  $\mu_m(T)$  is the maximum specific growth rate,  $\text{hr}^{-1}$ , and  $K_s(T)$  is the saturation constant (the value of  $S$  at which  $\mu = \mu_m(T)/2$ ) in  $\text{mg}/\ell$ . The Monod equation is an empirical expression of the relationship between the gross specific growth rate and the concentration of the growth limiting substrate. Although several alternative relationships have been proposed, the above expression is gaining widespread acceptance and provides an adequate description of mixed microbial systems (18,19,20,21). The maximum specific growth rate and saturation constant are written as they are to indicate that they are functions of temperature.

Cell decay is also assumed to be first order, where

$$r_{dX_v} = b_1(T)X_v \quad (2.4)$$

Cell decay is due to requirements of endogenous metabolism and maintenance energy, and the decay constant  $b_1(T)$ , is also a function of temperature. Maintenance energy is the energy required by cells to maintain their organization

and composition. Energy is required for such processes as motility, transport, overcoming osmotic pressure, and replacing essential compounds lost by natural decay. This results in less energy being available for synthesis and more carbon being given off as  $\text{CO}_2$ . Endogenous metabolism is the direct consequence of maintenance energy and results when there is no longer any exogenous substrate to provide maintenance energy requirements. During periods of food shortage, a cell will cannibalize its nonessential components to maintain essential compounds (22).

Cell death is also assumed to be first order with respect to viable cell concentration, where

$$r_{DX_V} = \gamma(T)X_V \quad (2.5)$$

and the specific death constant,  $\gamma(T)$ , is a function of temperature.

Therefore, the net rate of production of viable organisms is given by

$$r_{X_V} = \mu X_V - b_l(T)X_V - \gamma(T)X_V \quad (2.6)$$

or, substituting from equation (2.3),

$$r_{X_V} = \frac{\mu_m(T)S}{K_S(T)+S} X_V - b_l(T)X_V - \gamma(T)X_V \quad (2.7)$$

Equation (2.7) states that the net production rate of viable organisms is the difference between the gross rate at which such organisms are produced through substrate utilization and the rate at which viable organisms are lost by death and decay.

### 2.2.2 Microbial Cell Death

In a similar fashion, the net rate at which dead organisms are produced is the difference between the rate at which they are produced from the death of viable organisms and the rate at which they are lost to cellular decay ( $b_2(T)X_d$ )

$$r_{X_d} = \gamma(T)X_v - b_2(T)X_d \quad (2.8)$$

In this expression  $b_2(T)$  is the specific decay rate constant, and includes losses due to cell lysis and predation.

### 2.2.3 Substrate Utilization

Substrate utilization is assumed to occur at a rate which is proportional to the specific growth rate of the viable cells. That is,

$$r_s = \frac{\mu}{Y_g(T)} X_v \quad (2.9)$$

where  $Y_g(T)$  represents the true growth yield (the mass of cells formed per mass of substrate removed). This quantity cannot be observed directly because a portion of the cells are always lost to decay. Therefore it represents the quantity

of cells that would be formed in the absence of decay. It is also a function of temperature.

#### 2.2.4 Net Microbial Productivity

Substituting equation (2.9) into equation (2.6), an alternative expression for the net production rate of viable organisms is

$$r_{X_v} = Y_g(T)r_s - b_1(T)X_v - \gamma(T)X_v \quad (2.10)$$

Hence, since the total cell concentration is the sum of the viable and nonviable cell concentrations, the total rate at which cells are formed is obtained by combining equations (2.10) and (2.8)

$$\begin{aligned} r_X = r_{X_v} + r_{X_d} &= (Y_g(T)r_s - b_1(T)X_v \\ &\quad - \gamma(T)X_v) + (\gamma(T)X_v - b_2(T)X_d) \end{aligned}$$

or

$$r_X = Y_g(T)r_s - b_1(T)X_v - b_2(T)X_d \quad (2.11)$$

The death rate does not appear in this equation because it only serves to differentiate between the viable and nonviable cells. Since the two decay parameters  $b_1(T)$  and  $b_2(T)$  cannot



be determined individually, they are usually measured as an effective decay constant,  $b(T)$ , that applies to the total cell concentration. Hence

$$b(T)X = b_1(T)X_v + b_2(T)X_d \quad (2.12)$$

where  $b(T)$  can be measured. However, for this definition to be consistent with representation of the total cell concentration as the sum of the viable and dead components, it must also be assumed that  $b(T)$ ,  $b_1(T)$  and  $b_2(T)$  are equal. There is no experimental evidence available on the relative decay rates of the two types of cells. With this assumption, equation (2.11) for the net production of organisms becomes

$$r_X = Y_g(T)r_s - b(T)X \quad (2.13)$$

In the foregoing model the temperature dependent kinetic parameters are then  $\mu_m(T)$ ,  $K_s(T)$ ,  $b(T)$ ,  $\gamma(T)$  and  $Y_g(T)$ .

### 2.3 The Temperature Dependent Kinetic Parameters

The temperature dependence of four of the kinetic parameters,  $\mu_m(T)$ ,  $b(T)$ ,  $Y_g(T)$  and  $K_s(T)$ , has been widely investigated. However the temperature dependence of  $\gamma(T)$ , the rate constant for cell death, is not well documented. Hence it will be assumed to have a constant value of  $0.010 \text{ hr}^{-1}$ , which is based on available data (23).

The values of the remaining kinetic parameters depend not only on temperature but also on the type of culture, substrate and growth conditions. For the temperature range of interest in this study ( $10\text{ C} \leq T \leq 30\text{C}$ ), Figures 2.1-2.3 show some of the results for the variation of  $\mu_m$ ,  $b$  and  $Y_g$  with temperature. The yields of Friedman and Schroeder (27) and Garrett and Sawyer (26) are not true growth yields, but observed yields, which include the effect of decay. The observed yields, however, do illustrate the effect of temperature on the true growth yield.

As mentioned previously, the results depend on the nature of the microbial culture and growth conditions, as well as on temperature. The cultures used by Topiwala and Sinclair (24), Mennett and Nakayama (25), Garrett and Sawyer (in 26), Friedman and Schroeder (27), and Muck and Grady (28) were all grown continuously; while the cultures of Senez (29), Brown and Rose (30), and Ng et al (31) were grown under batch conditions. The types of cultures are A. aerogenes for Topiwala and Sinclair, and Senez, P. fluorescens for Mennett and Nakayama, E. coli for Ng et al, and C. utilis for Brown and Rose; while those used by Garrett and Sawyer, Friedman and Schroeder, and Muck and Grady were all mixed cultures. Other studies of the effect of temperature on one or more of the kinetic parameters were made by Borrow et al (32) for G. fujikuroi grown under batch conditions, Johnson

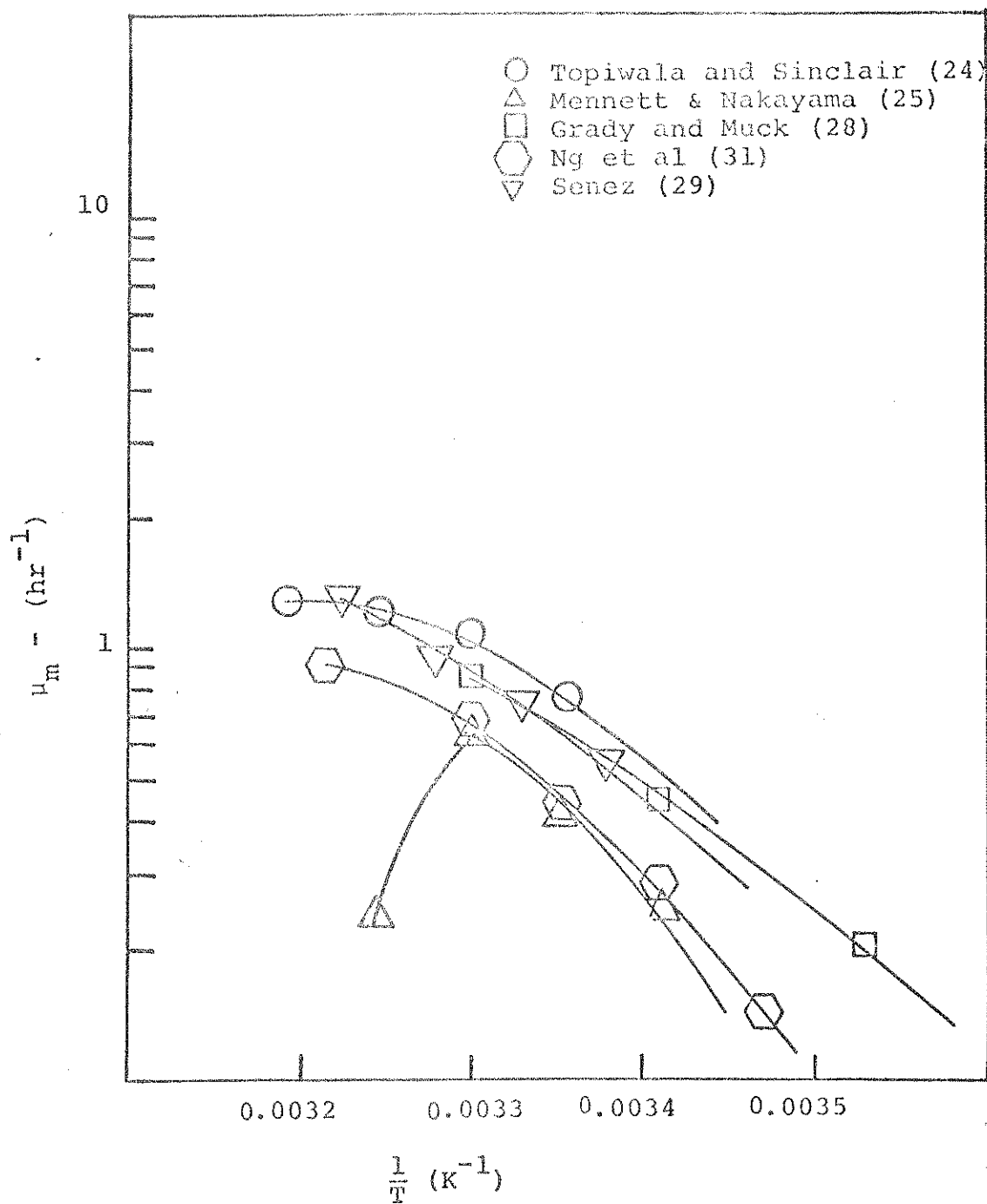


Figure 2.1 Variation of  $\mu_m$  with temperature.

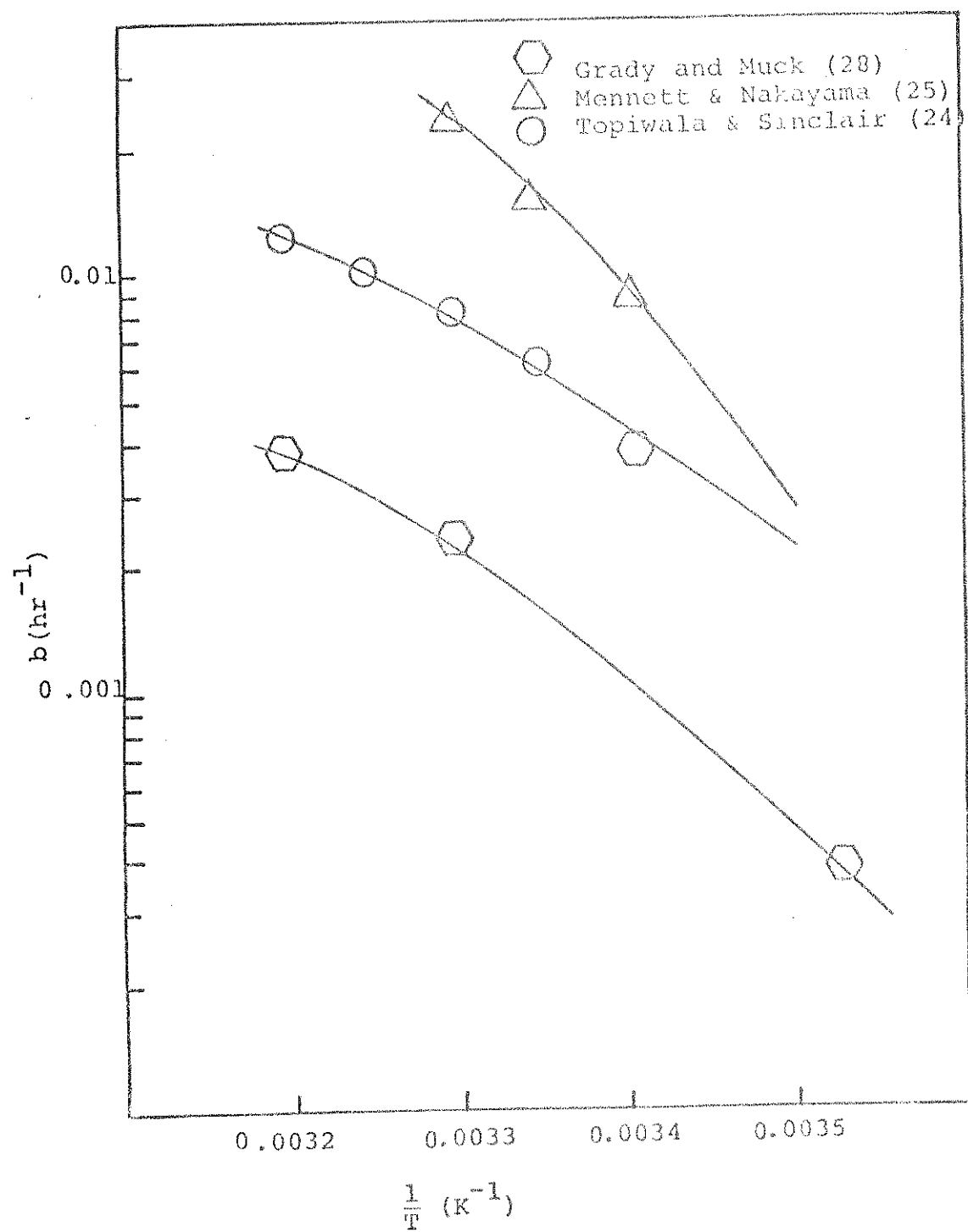


Figure 2.2 Variation of  $b$  with temperature.

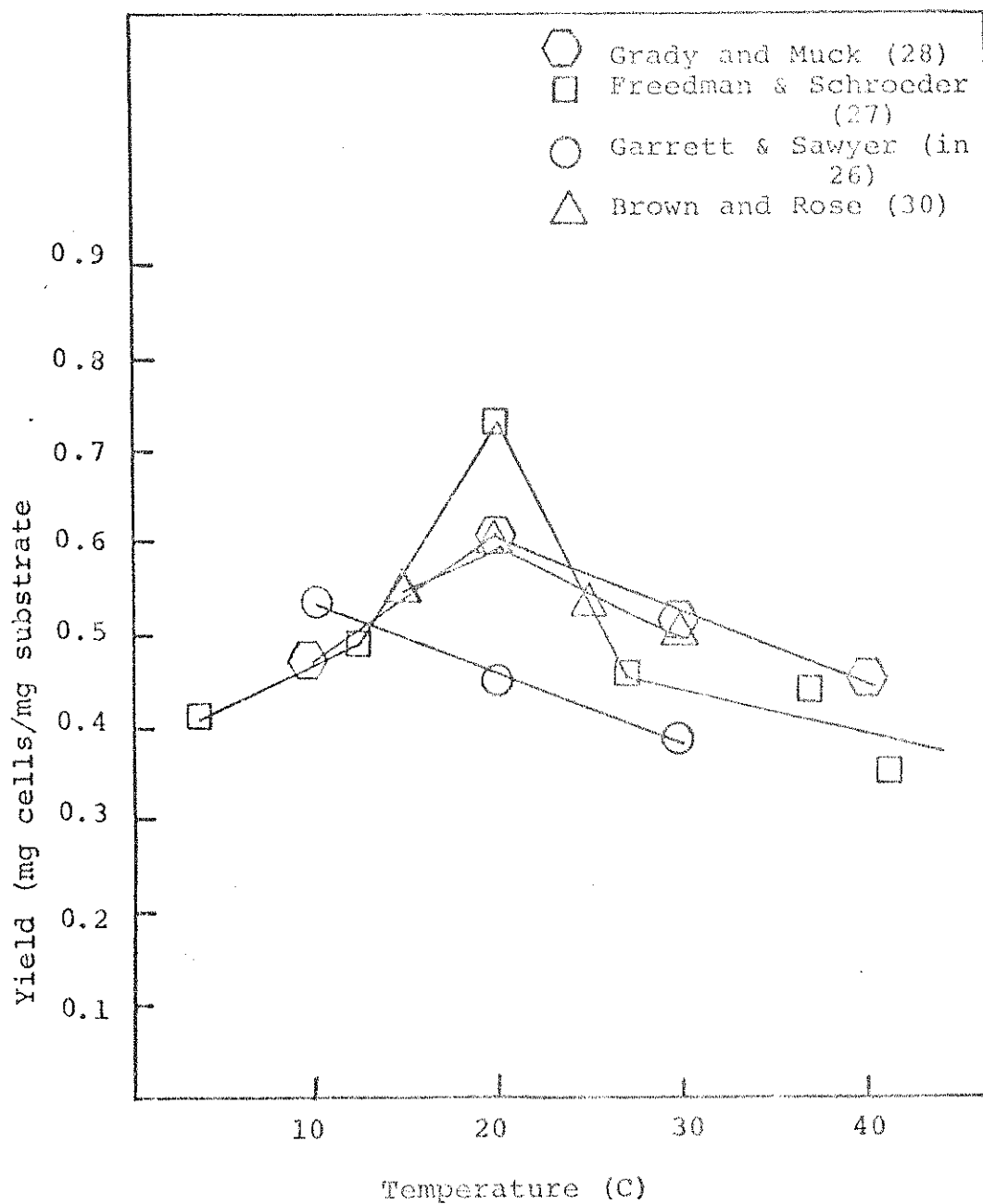


Figure 2.3 Variation of yield with temperature.

and Lewin (33) for E. coli grown under batch conditions, and Greene and Jezeski (34) for Pseudomonas No. 92 grown under batch conditions. These all predict trends similar to those shown in Figure 2.1. All cultures, with the exception of those grown by Greene and Jezeski which used lactose and those of Friedman and Schroeder which used sucrose, used glucose as the substrate off which the bacteria fed.

A plot of  $K_s(T)$  has not been included. Despite having been investigated (15,24,28,35,36), there remains uncertainty as to whether  $K_s$  increases or decreases with increasing temperature, with considerable variability existing among various organisms and growth conditions. At this time, it is felt that the most reasonable approach is to treat  $K_s$  as constant for the system. Values of  $K_s$  from various sources are listed in Table 2.1.

Returning to Figure 2.1 and recalling that the rate of growth of viable cells is given by

$$r_{GX_v} = \mu X_v \quad (2.2)$$

where  $\mu$ , the gross specific growth rate, is

$$\mu = \frac{\mu_m(T)S}{K_s + S} \quad (2.3)$$

it can be seen that the effect of increasing temperature is to increase the growth rate, that is, the higher the temperature, the faster the cells will reproduce. The rate of

Table 2.1 Reported and selected values of  $K_s$  for domestic waste

<u><math>K_s</math> (mg/l)</u>	<u>Source</u>
55	(37)
60	(37)
22	(15)
120	(38)
50-125	(41)

Selected Value 75 mg/l

decay of cells is given by

$$r_{dx} = b(T)X \quad (2.14)$$

So the effect on  $b$  of increasing temperature, Figure 2.2, suggests that, at higher temperatures, the cell must use more energy to maintain essential functions. The true growth yield,  $Y_g$ , reflects the ability of the bacteria to synthesize cell material from the substrate. Figure 2.3 indicates that  $Y_g$  increases with temperature up to approximately 20 C, after which it decreases with increasing temperature. As yet, there is no suitable explanation for this behavior.

Within the field of microbial kinetics, the expression most commonly used to quantify the effects of temperature upon reaction rates is the Arrhenius equation (39). This expression was originally proposed to describe the effect

of temperature on chemical reaction rates and was later extended to represent the effect of temperature on the rates of biological processes. The activation energy,  $E$ , was replaced by the quantity  $u_o$ , which is referred to as the temperature characteristic of the process (39), and the Arrhenius equation is expressed as

$$k_o = A_1 e^{-u_o/RT} \quad (2.15)$$

where  $k_o$  is the reaction velocity,  $\text{hr}^{-1}$ ,  $A_1$  is a constant,  $u_o$  is the temperature characteristic, cal/mole,  $R$  is the universal gas constant, cal/mole-K, and  $T$  is the absolute temperature K.

Values of the temperature characteristic have been determined by Grady and Muck (28) from the work of a number of investigators and range from 5,000 to 40,000 cal/mole for  $\mu_m(T)$  (Table 2.2a) and from 8,400 to 18,000 cal/mole for  $b(T)$  (Table 2.2b). The values selected for this study are intermediate and are characteristic of a domestic sewage treatment facility. The coefficient  $A_1$  is taken as  $10.67 \times 10^8$  for  $\mu_m$  and  $5.916 \times 10^7$  for  $b$ . Using the chosen coefficients with the Arrhenius equation, values of  $\mu_m$  equal to  $0.5 \text{ hr}^{-1}$  and  $b$  equal to  $0.0025 \text{ hr}^{-1}$  are obtained at 20 C. These values compare favorably with those shown in Table 2.3 for domestic sewage.



Table 2.2a Reported and selected values of the temperature characteristic for the maximum specific growth rate constant,  $\mu_m$ .

Temperature Range (C)	Temperature Characteristics (cal/mole)	Source
18-39.4	15,100	33
10-30	28,300	30
0-20	17,000	30
20-30	10,000	30
0-15	34,800	34
0-30	20,500	34
10-30	12,500	34
22-37	13,300	in28
20-30	16,600	25
25-40	8,400	24
23-37	10,900	29

Selected Value 12,500

Table 2.2b Reported and selected values of the temperature characteristic for the decay constant,  $b$ .

Temperature Range (C)	Temperature Characteristics (cal/mole)	Source
20-30	18,200	25
8-30	8,430	in28
10-30	13,900	28
25-40	9,000	24

Selected Value 13,900

Table 2.3 Representative values of  $\mu_m$  and  $b$  for mixed cultures growing in domestic sewage at 20 C.

$\mu_m$ (hr <sup>-1</sup> )	$b$ (hr <sup>-1</sup> )	Source
0.46	-	37
0.40	-	37
-	0.002	10
0.55	0.0025	38
0.40-0.60	-	41
-	0.0023	10

Unfortunately, no such expression can suitably describe the effect of temperature on  $Y_g$ . Therefore it was decided to use data available in the literature for the temperatures being considered ( $10 \leq T \leq 30$  C). However it was first necessary to determine a typical yield at 20 C for domestic sewage, since all the yields illustrated in Figure 2.3 are for cultures grown on a single substrate, rather than a mixed substrate such as occurs in domestic sewage. Values of  $Y_g$  for domestic sewage are given in Table 2.4, and a representative value of 0.5 (mg cells/mg substrate utilized) was selected. This allows adjustment of the true growth yields obtained by Grady and Muck to what was felt to be a representative range of values for the variation of  $Y_g$  with temperature for domestic sewage. The corrected values are listed in Table 2.5. This information was input as data to the solution, since the system was only investigated at discrete temperatures.

Table 2.4 Representative values of  $Y_g$  for mixed cultures growing on domestic sewage

<u><math>Y_g</math> (mg cells/mg sub.)</u>	<u>Source</u>
0.67	10
0.50	38
0.50	10
0.67	10
0.40-0.60	41

Table 2.5 Variation of the true growth yield,  $Y_g$ , with temperature.

<u>Temperature (C)</u>	<u><math>Y_g</math> (mg cells/mg substrate)</u>
10	0.392
15	0.446
20	0.500
25	0.465
30	0.431
35	0.401

Table 2.6 summarizes the expressions and values used for the kinetic parameters in this study.

#### 2.4 Mathematical Model of the CMAS

The governing equations for a CMAS may be obtained by performing mass balances on the system. Although the general form of the balance is

$$\text{Input} = \text{Output} + \text{Reaction} + \text{Accumulation}$$

steady state conditions are appropriate to this study, in which case the accumulation term is zero.

The concentration of viable cells in the reactor may be obtained by performing a mass balance on the substrate

$$FS_0 + \alpha FS = FS + \alpha FS + r_s V \quad (2.16)$$

Substituting equation (2.9) for  $r_s$  and simplifying leads to

$$X_v = \frac{Y_g (S_0 - S)}{\mu \bar{t}} \quad (2.17)$$

where  $\bar{t}$  is defined as the hydraulic residence time, ( $\bar{t} \equiv V/F, \text{hr}$ ). For simplicity, the temperature dependence of

Table 2.6 Values and expressions used for the temperature dependence of the bacterial kinetic parameters.

$$\mu_m(T) = 10.67 \times 10^8 \exp(-12,500/RT) \text{ hr}^{-1}$$

$$b(T) = 5.916 \times 10^7 \exp(-13,900/RT) \text{ hr}^{-1}$$

$$K_s = 75 \text{ mg/l}$$

$$\gamma = 0.010 \text{ hr}^{-1}$$

<u>Temperature (C)</u>	<u>Y<sub>g</sub> (mg cells/mg substrate)</u>
10	0.392
15	0.446
20	0.500
25	0.465
30	0.431

the kinetic parameters, for example  $Y_g(T)$ , will henceforth not be shown.

An expression for  $\mu$ , the specific growth rate constant for viable cells, can be obtained by performing a mass balance on the viable organisms in the reactor. The mass of organisms in the influent is usually very small and may be neglected. So the mass balance becomes

$$F_r X_{vr} = (F + F_r) X_v - r_{GX_v} V + r_{DX_v} V + r_{dX_v} V \quad (2.18)$$

The generation of viable cells is from growth

$$r_{GX_v} = \mu X_v \quad (2.2)$$

and the loss is due to decay and death

$$r_{dX_v} = b_1 X_v \quad (2.4)$$

$$r_{DX_v} = \gamma X_v \quad (2.5)$$

Substituting  $F_r = \alpha F$  and from equations (2.2), (2.4) and (2.5), and remembering that  $b_1 = b$ , equation (2.18) becomes

$$\alpha F X_{vr} = F(1+\alpha) X_v - \mu X_v V + \gamma X_v V + b X_v V \quad (2.19)$$

and rearranging,

$$\mu = (1 + \alpha - \alpha X_{vr}/X_v) \left(\frac{1}{t}\right) + \gamma + b \quad (2.20)$$

The sludge age, or mean cell residence time can be related to the growth of organisms by performing a mass balance for the viable organisms in the settler, remembering that because both underflows come out together, the viable waste cell concentration  $X_{vw}$  is the same as the viable recycle cell concentration  $X_{vr}$

$$(F + F_r)X_v = (F_r + F_w)X_{vr} + (F - F_w)X_{ve} \quad (2.21)$$

Substituting for  $F_r$  in terms of  $\alpha$  and rearranging

$$\frac{F_w X_{vr}}{F X_v} + \left(1 - \frac{F_w}{F}\right) \frac{X_{ve}}{X_v} = 1 + \alpha - \alpha \frac{X_{vr}}{X_v} \quad (2.22)$$

Substituting equation (2.22) in equation (2.20), one obtains

$$\mu = \left[ \frac{F_w X_{vr}}{F X_v} + \left(1 - \frac{F_w}{F}\right) \frac{X_{ve}}{X_v} \right] \frac{1}{(V/F)} + \gamma + b \quad (2.23)$$

or multiplying through the bracketed term by  $F$ , the specific growth rate is

$$\mu = \left[ \frac{F_w X_{vr}}{X_v} + (F - F_w) \frac{X_{ve}}{X_v} \right] \frac{1}{V} + \gamma + b \quad (2.24)$$

Equation (2.24) can be put in terms of the total cell concentrations by realizing that the viable cells in the reactor will be dispersed evenly throughout the suspended solids. When these solids reach the settler they will settle without regard to live or dead cells. Therefore

$$\frac{X_{vr}}{X_v} = \frac{X_r}{X} \quad (2.25)$$

and

$$\frac{X_{ve}}{X_v} = \frac{X_e}{X} \quad (2.26)$$

Equations (2.25) and (2.26) can be substituted into equation (2.24), the specific growth rate, to obtain

$$\mu = \left[ \frac{F_w X_r}{X} + (F - F_w) \frac{X_e}{X} \right] \frac{1}{V} + \gamma + b \quad (2.27)$$

Similarly, equation (2.22) becomes

$$\frac{F_w X_r}{F X} + \left( 1 - \frac{F_w}{F} \right) \frac{X_e}{X} = 1 + \alpha - \alpha \frac{X_r}{X} \quad (2.28)$$

The mean cell residence time,  $\theta_c$ , is defined as the total microbial mass in the treatment system divided by the total microbial mass withdrawn from the system per unit time. Assuming the mass of organisms held in the settler is



small compared to the mass in the reactor, the total mass equals the volume times the total cell concentration,  $X$ . Furthermore, the mass of solids withdrawn from the system is the sum of those cells wasted intentionally plus those that are lost in the effluent. That is, the amount of solids withdrawn is  $F_w X_r + (F - F_w) X_e$ , in which case  $\theta_c$  is

$$\theta_c = \frac{VX}{F_w X_r + (F - F_w) X_e} \quad (2.29)$$

The utility of the mean cell residence time can be seen from equation (2.28). Multiplying both sides of this equation by  $F/V$  and substituting from equation 2.29 yields

$$(1 + \alpha - \alpha X_r/X)/\bar{t} = 1/\theta_c \quad (2.30)$$

Substituting equations (2.25) and (2.30) into equation (2.20), the specific growth rate constant may then be expressed as

$$\mu = 1/\theta_c + \gamma + b \quad (2.31)$$

Hence, in a CMAS the mean cell residence time controls the growth rate.

Substituting equation (2.31) into equation (2.17), the viable cell concentration in the aeration tank is

$$X_v = \frac{Y_g(S_o - S)}{(1/\theta_c + \gamma + b)\bar{t}} \quad (2.32)$$

In addition, substituting for  $\mu$  from equation (2.31) into the Monod expression (equation 2.3) and rearranging, an expression is obtained for the final effluent concentration which is independent of the influent concentration and depends only on  $\theta_c$  for a fixed system

$$S = \frac{(1/\theta_c + \gamma + b)K_s}{\mu_m - (1/\theta_c + \gamma + b)} \quad (2.33)$$

To obtain the total concentration of cells in the aeration tank, the concentration of dead cells in the reactor must be known. The concentration of dead cells may be obtained by performing a mass balance on the dead cells.

$$\alpha F X_{dr} = F X_d + \alpha F X_d - r_{X_d} V \quad (2.34)$$

Rearrangement and substitution of equation (2.8) yields

$$(1 + \alpha - \alpha X_{dr}/X_d) = \gamma X_v/X_d \bar{t} - b \bar{t} \quad (2.35)$$

Because all cells settle together in the settler, the ratio of the dead cells in the underflow to the dead cells in the flow to the settler will be the same as the ratio of total cells in the underflow to total cells in the settler inflow

$$\frac{X_{dr}}{X_d} = \frac{X_r}{X} \quad (2.36)$$

Substituting equation (2.36) into equation (2.35) and combining with equation (2.30), the dead cell concentration may be expressed as

$$X_d = \frac{\gamma X_v}{1/\theta_c + b} \quad (2.37)$$

Since the total cell concentration in the aeration tank is the sum of the live and the dead cell concentrations, equations 2.1 and 2.37 may be combined to obtain

$$X = X_v \left[ 1 + \frac{\gamma}{1/\theta_c + b} \right] \quad (2.38)$$

Substituting from equation (2.32) for the viable cell concentration and rearranging, the total cell concentration may be expressed as

$$X = \frac{Y_g (S_o - S)}{(1/\theta_c + b) \bar{t}} \quad (2.39)$$

One of the primary objectives of a CMAS is to provide a high quality effluent, one that is low both in soluble substrate concentration and in suspended solids concentration. To do this a settler is used and cells are removed from the bottom as a concentrated underflow. A portion of those concentrated cells must be wasted if the system is to

maintain steady state. A major expense in the treatment of wastewater comes from the disposal of those cells. Therefore it would be advantageous to have an expression relating the mass wastage rate to other parameters of the system.

The mass flow rate of waste solids is given by  $F_w X_r$ , so that an expression for that term may be obtained by rearranging equation (2.32)

$$F_w X_r = VX/\theta_c - (F-F_w)X_e \quad (2.40)$$

Substituting for the total cell concentration from equation (2.39)

$$F_w X_r = \frac{FY_g(S_o - S)}{1 + b\theta_c} - (F-F_w)X_e \quad (2.41)$$

Equation (2.41) determines the mass of suspended solids that must be disposed of.

## 2.5 Oxygen Requirements

Oxygen is required by the bacteria for cell respiration and synthesis. The rate at which oxygen is used by the bacteria is designated as  $r_{O_2}$  (mg/l/hr) and may be found from a mass balance on oxygen demand for the system.

$$FS_o + \alpha FS + \alpha F\beta X_r = FS + \alpha FS + (1 + \alpha)F\beta X + r_{O_2} V \quad (2.42)$$

$FS_0 + \alpha FS$  represents the oxygen demand of the soluble substrate in the influent flows;  $\alpha F\beta X_r$  is the oxygen demand of the cells in the recycle flow;  $FS + \alpha FS$  is the oxygen demand of the substrate in the effluent flow from the aeration tank;  $(1+\alpha)F\beta X$  is the oxygen demand of the cells in the flow from the aeration tank; and  $r_{O_2} V$  is the rate of oxygen utilization by the cells in the aeration tank. The quantity  $\beta$  is the oxygen equivalent of cells formed ( $\text{mgO}_2/\text{mg cells}$ ) and represents the amount of oxygen required to completely oxidize the cells to  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . It is subject to considerable variation. Theoretically it should be a function of growth conditions of the cells, but there is presently little known about the nature of the function. The most common approach involves assigning  $\beta$  a value of 1.41, which is the theoretical oxygen demand associated with the empirical cell formula  $\text{C}_5\text{H}_7\text{O}_2\text{N}$  (42). Rearrangement and simplification of equation (2.42) yields

$$r_{O_2} \bar{t} = S_0 - S - [1 + \alpha - \alpha(X_r/X)]\beta X \quad (2.43)$$

Substituting from equation (2.30), equation (2.43) becomes

$$r_{O_2} = (S_0 - S)/\bar{t} - \beta X/\theta_c \quad (2.44)$$

Substituting for the cell concentration  $X$  from equation (2.39), the rate of oxygen uptake per unit volume may be expressed as

$$r_{O_2} = \frac{(S_o - S)(1 + b\theta_c - \beta Y_g)}{\bar{t}(1 + b\theta_c)} \quad (2.45)$$

The rate of oxygen uptake for the entire reactor is then

$$r_{O_2} V = \frac{F(S_o - S)(1 + b\theta_c - \beta Y_g)}{(1 + b\theta_c)} \quad (2.46)$$

This expression determines the rate of oxygen demand by the cells in the aeration tank as a function of sludge age. Since this demand cannot be completely satisfied by oxygen dissolved in the influent stream, additional oxygen must be supplied to the system. This is done by aeration devices which bring air into contact with the wastewater, thereby allowing transfer of oxygen to the water.

Oxygen is a gas which is slightly soluble in water. The solubility decreases with increasing temperature, and the rate of transfer of oxygen to the water is determined by conditions at the liquid film. The situation is as shown in Figure 2.4. The film provides a resistance to gas transfer and is the rate limiting factor. The resistance is described in terms of the reciprocal of a mass transfer coefficient  $K_L$ , and the mass transfer of oxygen per unit time is expressed as

$$N' = K_L aV(c^* - c) \quad (2.47)$$

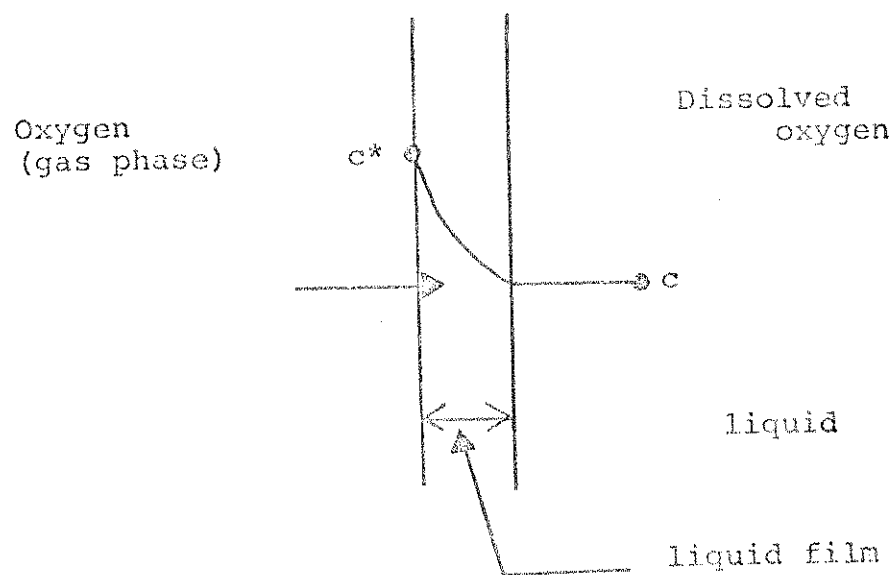


Figure 2.4 Oxygen transfer in liquids

The quantity  $N'$  is the mass of oxygen transferred per unit time for the entire reactor;  $c^*$  is the saturation concentration of oxygen, that is the concentration which would be present in the water at equilibrium (mg/l);  $c$  is the actual oxygen concentration in the water (mg/l);  $V$  is the reactor tank volume (l); and  $a$  is the interfacial surface area between the gas phase and the liquid. Because the interfacial surface area,  $a$ , is generally unknown, it is combined with  $K_L$  into an overall volumetric mass transfer coefficient with units of reciprocal time (42).

Equation (2.47) will be applied for steady-state conditions, in which case the rate at which oxygen is used is equivalent to the rate at which it is supplied ( $r_{O_2} V = N'$ ) and  $c$  remains constant. These conditions are appropriate to the present problem. In addition to being diminished by an increase in temperature, the solubility of oxygen in water is also adversely affected by the presence of dissolved solids in the system. The combined effect of temperature and dissolved solids can be modeled by the equation of Gameson and Robertson (43)

$$c^* = \frac{475 - 2.65S_D}{33.5 + T} \quad (2.48)$$

where  $S_D$  is the concentration of dissolved solids (g/l), and  $T$  is the system temperature (C). Strictly speaking, equation (2.48) is for mixtures of pure water and sea water,



although it is widely used for wastewater. For domestic wastes it is known to provide suitable results; however, it should be used with caution for industrial wastes (43).

For bubble aeration, the air is introduced to the system at a substantial depth below the surface. There are then two effects on the bubble as it rises. First, the hydrostatic pressure on the bubble is reduced, which in turn reduces the partial pressure of the oxygen within the bubble. Second, oxygen is being constantly transferred from the bubble to the surrounding water, which reduces the mole fraction of oxygen in the bubble and hence reduces the partial pressure. Collectively, these effects contribute to lessening the saturation concentration of oxygen in the system as the bubble rises. It is therefore necessary to compute a mean saturation concentration,  $c_m^*$ , corresponding to the mid-depth value in the tank. Oldshue (44) has proposed the following expression

$$c_m^* = c^* \left[ \frac{P'}{29.4} + \frac{O_t}{42} \right] \quad (2.49)$$

where  $P'$  is the absolute pressure (psi) at the depth of air release and  $O_t$  is the percent of oxygen in the air leaving the tank (usually assumed to be 18.9% on the basis of 10% removal).  $c_m^*$  should be used in equation (2.47). It provides an average saturation concentration throughout the tank.

Eckenfelder (45,46), through dimensional analysis, showed that the mass transfer coefficient  $K_L$  for bubble aeration could be correlated as a function of the dimensionless Sherwood and Reynolds numbers. In addition, the interfacial area for transfer per unit volume of liquid can be related to the gas flow rate per bubble aeration device and to the dimensions of the tank. By combining the aforementioned relations, an expression for the effects of depth of bubble release and gas flow rate on the overall volumetric mass transfer coefficient ( $K_L aV$ ) may be obtained. This expression is of the form

$$K_L aV = K^* q^{1-n} z^{m_a} \quad (2.50)$$

where  $K^*$  is a system constant,  $q$  is the gas flow rate per bubbler unit ( $\text{ft}^3/\text{min}$ ),  $z$  is the depth of gas release (ft), and  $K_L aV$  is in  $\text{ft}^3/\text{hr}$ . The exponents  $m_a$  and  $n$  must be empirically determined.

Both  $K^*$  and  $K_L a$  are functions of temperature, and the effect of temperature on  $K^*$  is assumed to be proportional to the effect of temperature on  $K_L a$ .  $K_L a$  can be related to the temperature by

$$(K_L a)_T = (K_L a)_{20} \theta_K^{T-20} \quad (2.51)$$

where  $\theta_K$  is the temperature coefficient, where an accepted

value is 1.024 (46), and  $T$  is the temperature, C. Therefore the effect of temperature on  $K$  can be written as

$$K_T^* = K_{20}^* \theta_K^{T-20} \quad (2.52)$$

Since the oxygen requirements determine what  $K_L a$  must be to provide oxygen and maintain the dissolved oxygen requirements, equation (2.52) must be used in equation (2.50) to completely account for the effect of temperature on oxygen requirements.

The value of  $c$  should be maintained around 2.0 mg/l to avoid a deleterious effect on the dissolved oxygen concentration in the stream when the wastewater is finally discharged.

The power requirements for aeration of an activated sludge system may be determined from a relation recommended by Kalinske (47).

$$P = 0.30 Q (P_c/P_a)^{0.28-1} \quad (2.53)$$

where  $P$  is the power required (HP),  $P_a$  is the atmospheric absolute pressure (14.7 psi at sea level),  $Q$  is the total air flow rate, and  $P_c$  is the absolute pressure of compression, which is the hydrostatic head above the air outlet plus losses in lines and fittings between the compressor and the outlet, plus the head loss in the outlet itself, plus atmospheric pressure.  $P_c$  is taken as 21.7 psia (47). For

purposes of calculation, the air transfer system must be specified. There are three general types of aeration systems. They include bubble aeration (air is passed through devices which break it up by forcing it through small holes), bubble aeration with mechanical agitation (rotating impellers are used to break up the bubbles as they are released from the passive bubble aeration device), and surface aerators (an impeller is used to agitate the liquid at the surface). In the surface aerator, air is transferred by splashing the liquid through the air and the process is enhanced by the increased surface area caused by turbulence. Since surface aerators must be limited to regions where icing is not a problem, they will not be considered in this study. Passive bubble aeration devices were chosen, both for simplicity and availability of information. In particular, the devices chosen are called spargers, and they release bubbles which are approximately 63.5 mm in diameter. A rectangular tank of depth 16 ft will be used, and the spargers will be evenly spaced one foot above the bottom of the tank.

To determine the number of spargers necessary, a base system was established for a temperature of 20 C. The oxygen demand of the system is given by equation (2.46), which at steady state equals the amount of oxygen transferred as given by equation (2.47). The saturation concentration,  $C_m^*$ , can be calculated from equations (2.48) and (2.49) for an air release depth of 15 feet. The actual concentration is taken as 2.0 mg/l. Therefore,  $K_L a$  can be determined from

equation (2.47). From the work of Eckenfelder (46), a mid-range value of  $0.5 \text{ lbO}_2$  transferror/sparger was chosen which gives an air flow rate of 6 cfm, from Figure 2.5. Therefore, the number of spargers required as a function of the sludge age can be determined by dividing the oxygen requirement by the amount of oxygen transferred per sparger, Figure 2.6.  $K^*$  can also be determined from knowing  $K_L a$  and the air flow rate.  $K^*$  was found to be 134.4.

From Figure 2.6 the number of spargers was chosen as 400 to provide adequate aeration for the upper limit of sludge age (15 days) and to allow for the increased aeration requirements at elevated temperatures. With this specified, the required air flow rate and power requirements can be determined as a function of temperature.

## 2.6 Mathematical Model of the Settling Tank

### 2.6.1 Clarification and Thickening

The settling tank in the activated sludge system has two functions which include production of an effluent which is relatively free of settleable solids and production of an underflow which contains, in high concentration, the solids which have been settled in the tank. Both clarification and thickening must be considered in determination of effluent quality. If it is assumed that effluent suspended solids

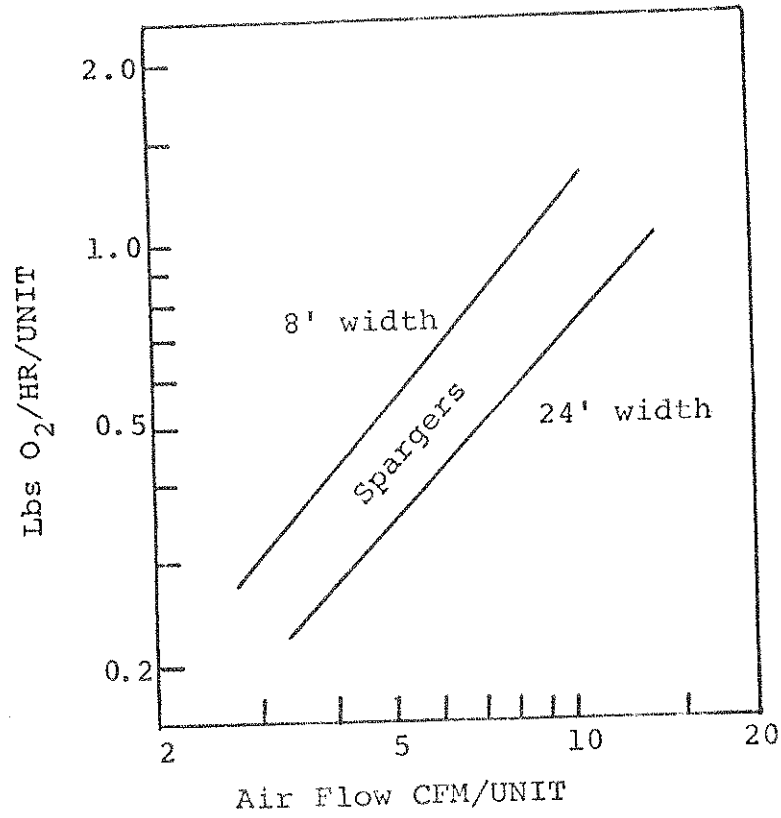


Figure 2.5 Effect of tank width on oxygen transfer in bubble aeration (46).

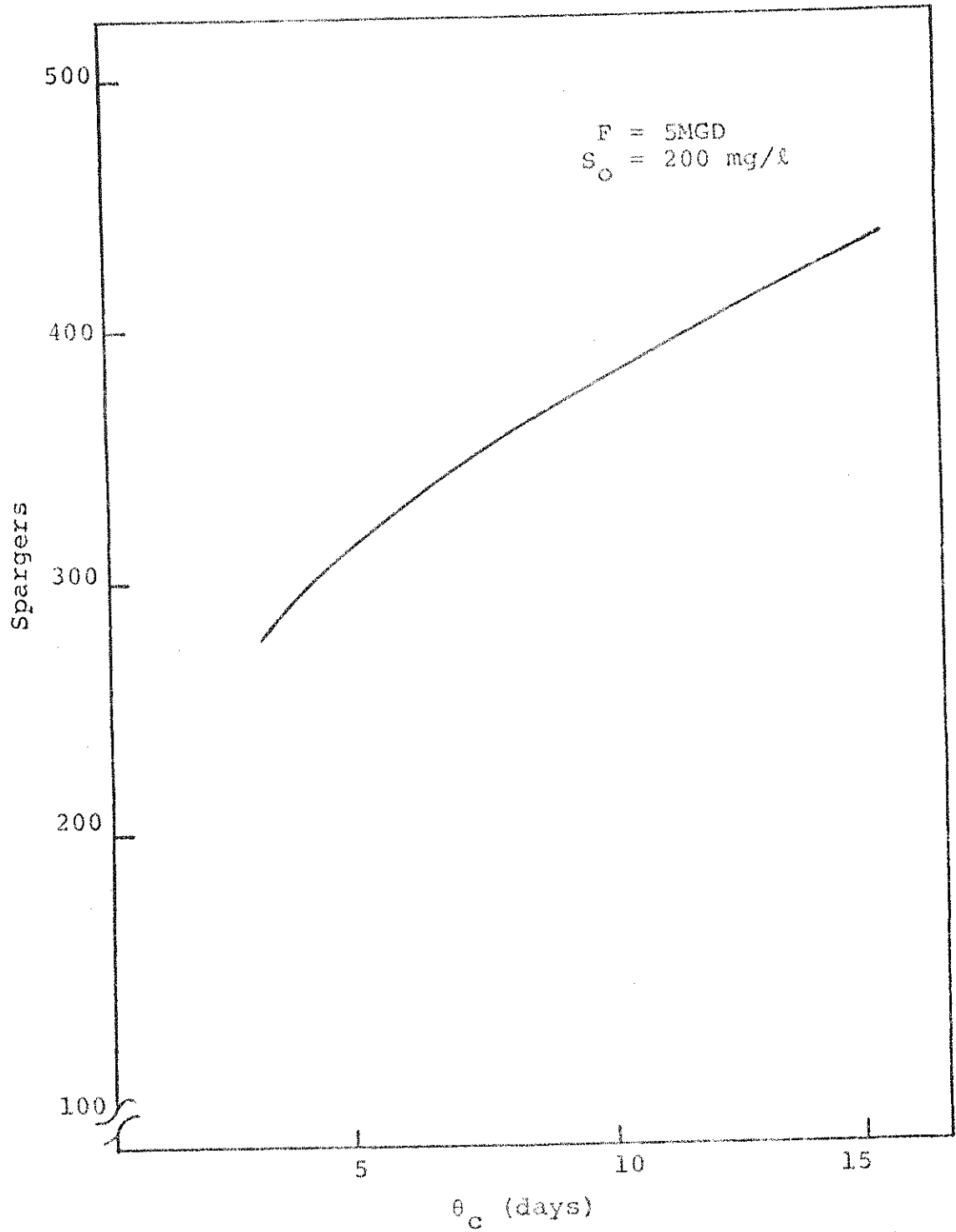


Figure 2.6 Number of spargers as a function of sludge age.

are the result of imperfect clarification and/or thickener failure, the effluent suspended solids concentration may be expressed as

$$X_e = X_{ec} + X_{et} \quad (2.54)$$

where  $X_{ec}$  is the contribution to  $X_e$  due to imperfect clarification (present during normal operation) and  $X_{et}$  is the contribution to  $X_e$  due to insufficient sludge withdrawal (thickener failure). Under normal operating conditions,  $X_{et}$  is equal to zero, and  $X_{ec}$  lies between 5 and 40 mg/l. The importance of the contribution of the suspended solids in the effluent to final effluent quality is illustrated in Figure 2.7. As shown by the figure, the total  $BOD^+$  of the effluent from an activated sludge plant is the dissolved BOD plus the BOD of the suspended solids. If it is assumed that 1 mg/l of suspended solids exerts a BOD of 0.6 mg/l, the final effluent quality,  $S_e$  can be expressed as

$$S_e = S + 0.6 (X_e) \quad (2.55)$$

### 2.6.2 The Clarification Model

Several empirical expressions have been proposed for

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<sup>+</sup>BOD is the biological oxygen demand of the waste. It is a measure of the oxygen required to convert the waste to bacteria,  $CO_2$  and  $H_2O$ .



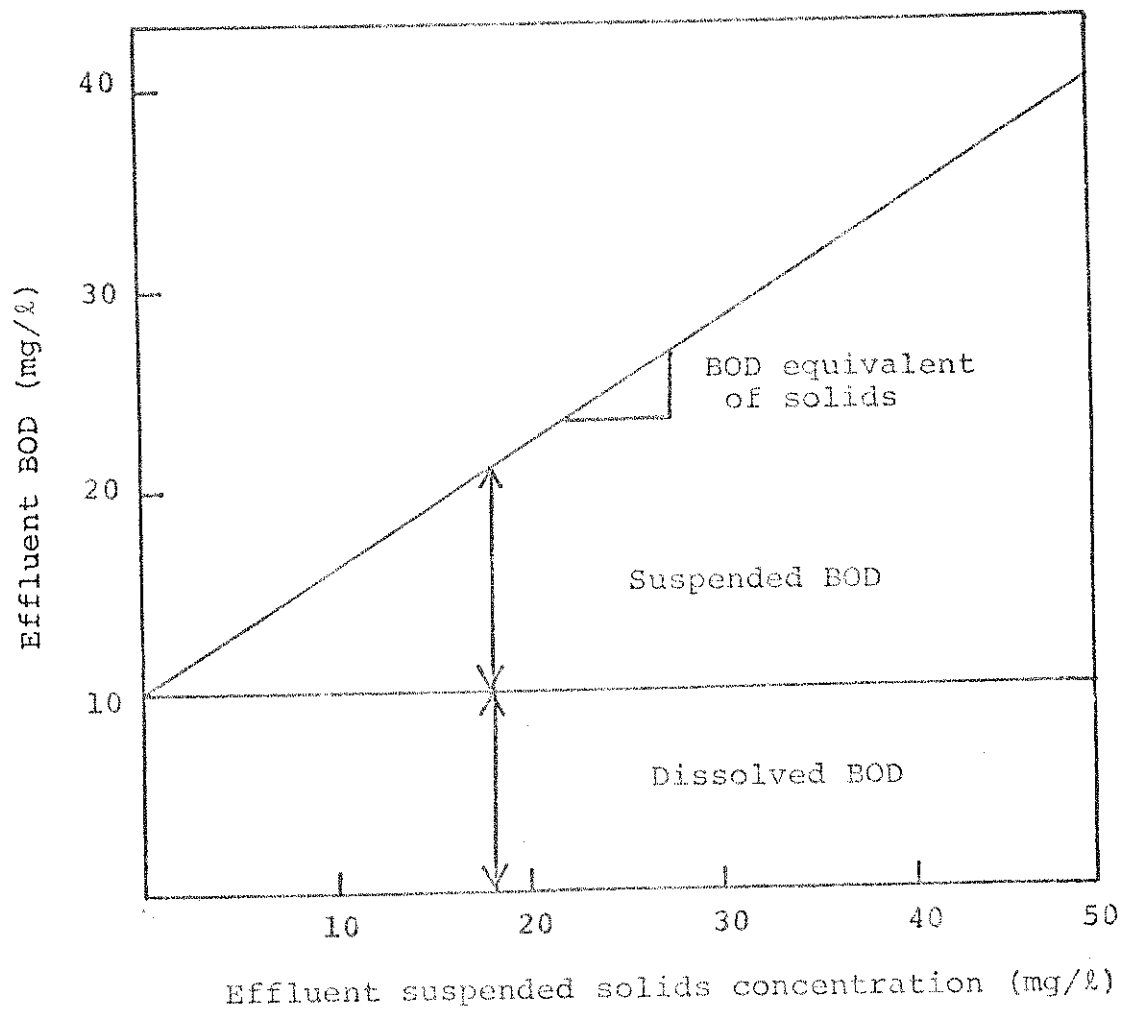


Figure 2.7 Effect of effluent suspended solids on quality of effluent from activated sludge plant (53).

the determination of  $X_{ec}$  (48,49,50,51,52). These include predictions that give opposing trends in the amount of suspended solids lost to the effluent by clarification. In particular, the expression developed by Tarrer(52) from data taken by Pflanz (49).

$$X_{ec} = 6.555 X(F-F_w)/A \quad (2.56)$$

where  $F$  and  $F_w$  are in millions of gallons per day differs considerably from the expression developed by Agnew (48).

$$X_{ec} = \frac{382(F-F_w/A)^{0.12}(FS_o/XV)^{0.27}}{X^{0.35} \bar{t}} \quad (2.57)$$

where  $F$  and  $F_w$  are in gal/day and  $\bar{t}$  is in hours.

The expression of Tarrer predicts increasing suspended solids with increasing cell concentration in the aeration tank, while that of Agnew shows decreasing suspended solids with increasing  $X$ . The trends are shown in Figure 2.8. Other expressions available predict trends similar to either that of Agnew or Tarrer, so it would seem that the performance of the settler is system specific. That is, different settlers perform differently with respect to clarification, and at this point in time it is not possible to specify the operating characteristics which determine those differences.

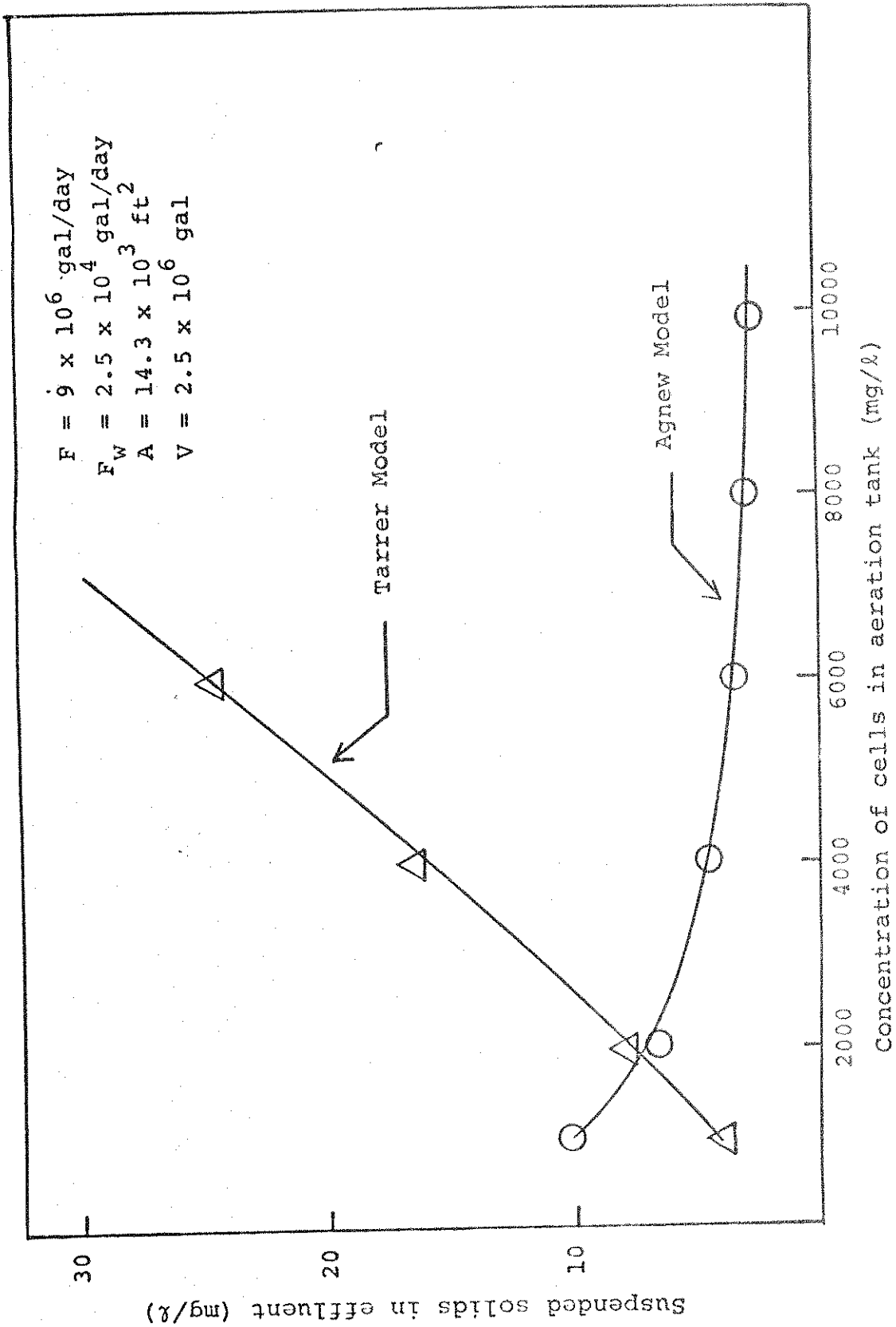


Figure 2.8 prediction of suspended solids in effluent by Agnew (48) and Tarrer (52) models.

To account for the temperature dependence of the settling particles, one assumes that they settle according to Stokes law

$$u_p = \frac{2g D_p^2 (\rho_p - \rho_f)}{9\mu_f} \quad (2.58)$$

where  $u_p$  is the settling velocity of the particle;  $D_p$  is the diameter of the particle;  $\rho_p$  and  $\rho_f$  are the density of the particle and the fluid, respectively;  $\mu_f$  is the fluid viscosity, and  $g$  is the acceleration of gravity. Stokes law was developed for spherical particles with a Reynolds number much less than one. The Reynolds number for bacterial flocs of up to 1 mm in diameter settling in water at 20 C will fit this requirement. Although the bacteria are not precisely spherical and their motion may be influenced by inertia effects, it is important to note that we are not concerned with the actual settling velocity, but only with the effect of temperature on this velocity. Since the density of the fluid and the particle are not strong functions of temperature,  $\mu$  is the only variable for which the influence of temperature need be considered. Equation (2.58) can be rearranged to show this

$$(u_p \mu_f)_{T_1} = \frac{2g D_p^2 (\rho_p - \rho_f)}{9} = (u_p \mu_f)_{T_2}$$

or

$$(u_p \mu_f)_{T_1} = (u_p \mu_f)_{T_2} \quad (2.59)$$

The temperature dependence can be incorporated in the expressions for settling of the particles by assuming that the value of  $X_{ec}$  is inversely proportional to the settling velocity of the particle. That is, as the settling velocity increases, the amount of suspended solids lost to the effluent decreases (54,55).

Thus, the clarification expression of Tarrer becomes

$$X_{ec} = \frac{6.555X(F-F_w)}{A} \left( \frac{\mu_{fT}}{\mu_{fT_o}} \right) \quad (2.60)$$

where  $\mu_{T_o}$  is the viscosity of water at the temperature for which the expression was originally developed, in this case 15 C.

Similarly, the expression by Agnew can be rewritten as

$$X_{ec} = \frac{382 \left( \frac{F-F_w}{A} \right)^{.12} (FS_o/XV)^{.27}}{X^{.35} \bar{t}} \left( \frac{\mu_{fT}}{\mu_{fT_o}} \right) \quad (2.61)$$

where  $T_o$  is 20 C.

### 2.6.3 The Thickener Model

The thickener model is based upon the work of Coe and Clevenger (56), Dick (53,57,58,59), Vesilind (60,61) and

others. The thickener is concerned with the production of a concentrated underflow, both for recycle to the aeration tank and for wastage to some final disposal of the excess sludge produced. The model is used not only to calculate the settler underflow concentration,  $X_u$ , for given feed conditions and underflow rate, but also to calculate the effluent suspended solids concentration,  $X_{et}$ , that would result from thickener failure.

The total downward flux through a settler may be represented as the sum of a solids flux due to gravity settling of the solids,  $G_g$ , and a solids flux due to bulk downward movement of the liquid and solids relative to the settling tank walls,  $G_u$ . Hence

$$G_T = G_g + G_u \quad (2.62)$$

where  $G_T$  is the total downward flux through the settler (mg/l-gal)/ft<sup>2</sup>-day;  $G_g$  is the subsidence flux (mg/l-gal)/ft<sup>2</sup>-day; and  $G_u$  is the bulk flux (mg/l-gal)/ft<sup>2</sup>-day.

The flux due to gravity settling is expressed as

$$G_g = c_i v_i \quad (2.63)$$

where  $v_i$  is the gravity settling velocity (ft/sec) of the sludge at concentration  $c_i$ . Similarly, the flux due to the settler underflow is

$$G_u = c_i u \quad (2.64)$$

where  $u$  is the underflow velocity ( $u = \frac{\alpha F + F_w}{A}$ ). Therefore the total downward solids flux is given by

$$G_T = c_i v_i + c_i u \quad (2.65)$$

The nature of this relationship is represented by Figure 2.9, the origin of which is discussed in the following paragraphs. It can be seen from Figure 2.9 that the bulk flux,  $G_u$ , varies linearly with concentration, while the subsidence flux,  $G_g$ , is dependent upon both the concentration and settling characteristics.

In order to use equation 2.65, an expression must be obtained for the settling velocity,  $v_i$ . Since  $v_i$  represents the settling velocity at various concentrations, an expression of the form  $v_i = f(c_i)$  is required. Since the settling velocity is also a function of temperature, the following expression from Keinath (54) was employed

$$v_i = K \theta^{T^2} c_i^{-\beta_0} \quad (2.66)$$

where  $K$ ,  $\theta$  and  $\beta_0$  are constants,  $c_i$  is the suspended solids concentration (mg/l),  $T$  is the temperature (C) and  $v_i$  is

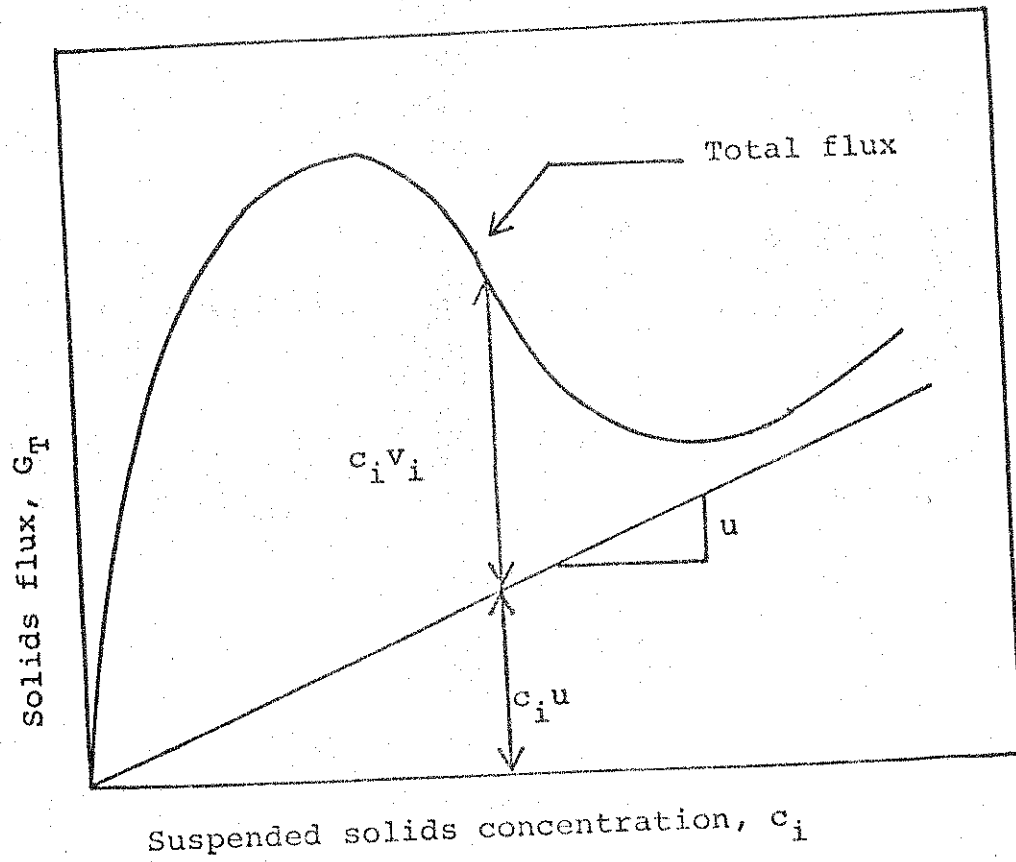


Figure 2.9 Total flux in settler as a function of suspended solids concentration (58)



the interfacial settling velocity (ft/min).<sup>+</sup>

This expression was obtained from Keinath (54), and it must be viewed as only a first step in modeling the effect of temperature on thickening. It accounts for only short term effects of temperature, that is, just the effect of temperature on the interfacial settling velocity and not the effect upon the physical and biochemical characteristics of the sludge.

Temperature does not strongly affect the thickening capacity. Dick (55) has also suggested that this will be true. Equation (2.66) can be regarded as an input to the system, so that if a better expression becomes available, it may be replaced.

Equation (2.66) may be substituted into equation (2.65) so that

$$G_T = K\theta^T c_i^{1-\beta_0} + c_i u \quad (2.67)$$

Several useful points which are associated with the flux-concentration curve may be inferred from equation (2.67). These parameters are shown in Figure 2.10 where  $G_L$  is the limiting solids handling capacity;  $c_L$  is the suspended solids concentration of the layer having a minimum transmitting capacity;  $c_m$  is the minimum value of the suspended

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<sup>+</sup>The interfacial settling velocity is the settling velocity of a layer of solids across the settling tank.

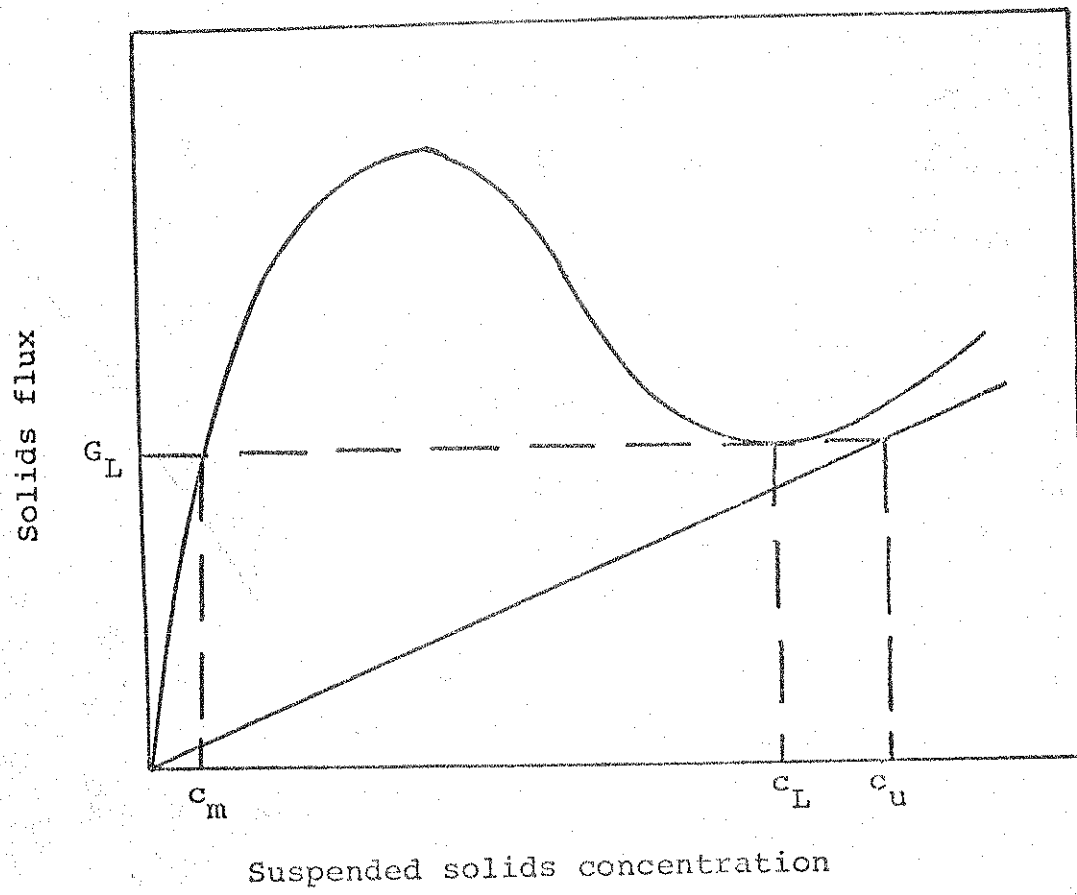


Figure 2.10 Characterization of the flux curve.

solids concentration in the final settler feed for which  $G_L$  is the limiting solids handling capacity; and  $c_u$  is the maximum underflow concentration attainable without loss of solids to the effluent.  $G_L$ ,  $c_m$ ,  $c_L$  and  $c_u$  may be determined by graphical techniques, but a more exact technique is necessary to make the solution amenable to computer calculations. As can be seen from Figure 2.10, the following conditions apply at the limiting concentration,  $c_L$

$$\left. \frac{\partial G_T}{\partial c_i} \right|_{c_L} = 0; \quad \left. \frac{\partial^2 G_T}{\partial c_i^2} \right|_{c_L} > 0; \quad G_T = G_L; \quad c_i = c_L \quad (2.68)$$

Thus, from equation (2.67)

$$\left. \frac{\partial G_T}{\partial c_i} \right|_{c_L} = K\theta T^2 (1-\beta_o) c_i^{-\beta_o} + u = 0 \quad (2.69)$$

or, rearranging,

$$c_L = \left[ \frac{(\beta_o - 1) K\theta T^2}{u} \right] \frac{1}{\beta_o} \quad (2.70)$$

Differentiation of equation (2.70) gives

$$\left. \frac{\partial^2 G_T}{\partial c_i^2} \right|_{c_L} = -K\theta T^2 (1-\beta_o) \beta_o c_i^{-(\beta_o+1)} \quad (2.71)$$

If  $K$  is positive and  $\beta_0$  is greater than one, the second derivative obtained from equation (2.70) is positive and equation (2.70) is indeed the limiting solids flux.

The value of the limiting solids flux,  $G_L$ , is

$$G_L = v_L c_L + u c_L \quad (2.72)$$

or substituting from equation 2.68

$$G_L = K\theta^T c_L^{1-\beta_0} + u c_L \quad (2.73)$$

The value of  $c_m$ , the minimum suspended solids concentration, may be calculated by realizing that  $G_T$  is equal to  $G_m$  at  $c_m$ . Hence

$$c_L v_L = c_L u = c_m v_m + c_m u \quad (2.74)$$

or

$$c_m = \frac{K\theta^T c_L^{1-\beta_0} + u c_L}{K\theta^T c_m^{1-\beta_0} + u} \quad (2.75)$$

Finally, the maximum underflow concentration  $c_u$  is calculated from

$$c_u = \frac{G_L}{u} \quad (2.76)$$

#### 2.6.4 Prediction of Thickener Performance

Since  $G_L$ ,  $c_m$ ,  $c_u$  and  $c_L$  may be determined for a prescribed bulk settling velocity  $u$  and settling constants  $K$  and  $\beta_0$ , the total downward flux curve may be determined from equation (2.67) and used to predict the characteristics of the settler. For a prescribed flow rate,  $(1+\alpha)F$ , and applied solids concentration,  $X_a$ , to the thickener, the resultant underflow concentration,  $X_u$ , and effluent concentration due to thickener failure,  $X_{et}$ , may be calculated.

The total applied flux to the settler is composed of an applied flux due to imperfect clarification, which will be transmitted upward,  $G_{ec}$ , and an applied flux to the thickener,  $G_a$ .

$$G = G_a + G_{ec} \quad (2.77)$$

The applied flux to the settler is given by

$$G = \frac{(1+\alpha)FX}{A} \quad (2.78)$$

and the applied flux due to imperfect clarification is

$$G_{ec} = \frac{X_{ec}(F-F_w)}{A} \quad (2.79)$$

The applied flux to the thickener may also be represented in a similar fashion by

$$G_a = \frac{(1+\alpha)FX_a}{A} \quad (2.80)$$

where  $X_a$  is the apparent applied suspended solids concentration to the thickener.  $X_a$  is less than  $X$  due to loss of suspended solids over the final settler. The point  $(G_a, X_a)$  determines the region in which the settler is operating. Once this is known, the conditions under which the settler is operating may be determined. This may be illustrated graphically in Figure 2.11. Several operating regions may be defined on the flux curve in which the point  $(G_a, X_a)$  may lie.

For example, if the point  $(G_a, X_a)$  were in region I, the underflow concentration could be determined by drawing a horizontal line from the point  $(G_a, X_a)$  to the line  $G_u = uc_i$  and then reading the corresponding value for  $X_u$ . Similarly for region V. The effluent suspended solids concentration  $X_{et}$  is equal to zero because the applied flux,  $G_a$ , is less than the maximum flux for all values of concentration between  $X_a$  and  $X_u$ .

Consider a point lying in region III. For this case, the appropriate flux,  $G_a$ , is restricted by the relative minimum flux,  $G_L$ , occurring at  $c_L$ . Thus in order for the sludge to pass through the layer of concentration  $c_L$ , a limiting flux is imposed on the thickener such that the actual flux passed downward is just  $G_L$  and not  $G_a$ . The

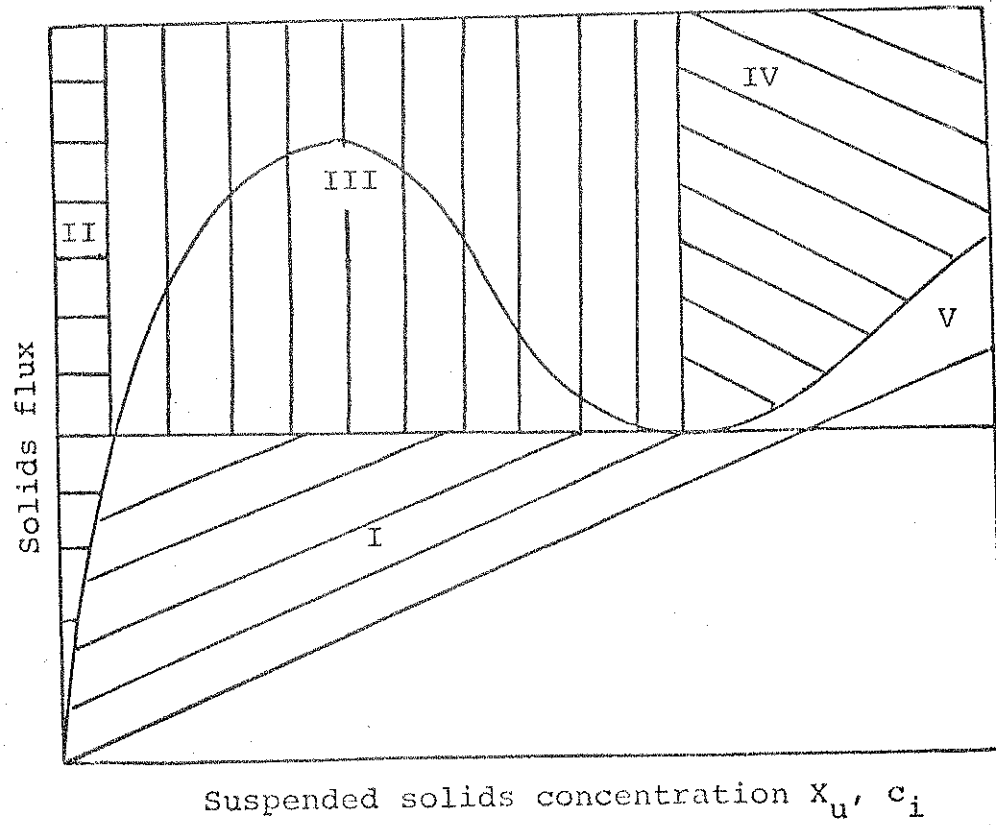


Figure 2.11 Regions for applied operating points(23)

difference between  $G_a$  and  $G_L$  is the flux transmitted upward,  $G_{et}$ . This results in the effluent solids component  $X_{et}$ . The underflow concentration will be  $X_u$ . Shown in Figure 2.12 are examples of the two conditions just discussed, while Figure 2.13 shows other operating regions.

$G_a$  could be calculated from equation (2.78) if the value for  $X_a$  were known. However, rearrangement of equation (2.75) and substitution of equations (2.76) and (2.77) allows  $G_a$  to be calculated from known values.

$$G_a = \frac{(1+\alpha)FX}{A} - \frac{(F-F_w)X_{ec}}{A} \quad (2.79)$$

The value for  $X_a$ , which is necessary to determine the operating region of the thickener, can then be determined by combining equations (2.78) and (2.79)

$$X_a = X - \left(\frac{X_{ec}}{1+\alpha}\right) \left(1 - \frac{F_w}{F}\right) \quad (2.80)$$

The solids concentration,  $X_a$ , is an apparent feed concentration to the thickener, due to loss of solids to the effluent by imperfect clarification.

Equations (2.79) and (2.80) define the operating point of the thickener model. Thus,  $X_u$  and  $X_{et}$  may be determined in accordance with the particular region in which  $(X_a, G_a)$  lies. This is summarized in Table 2.7.



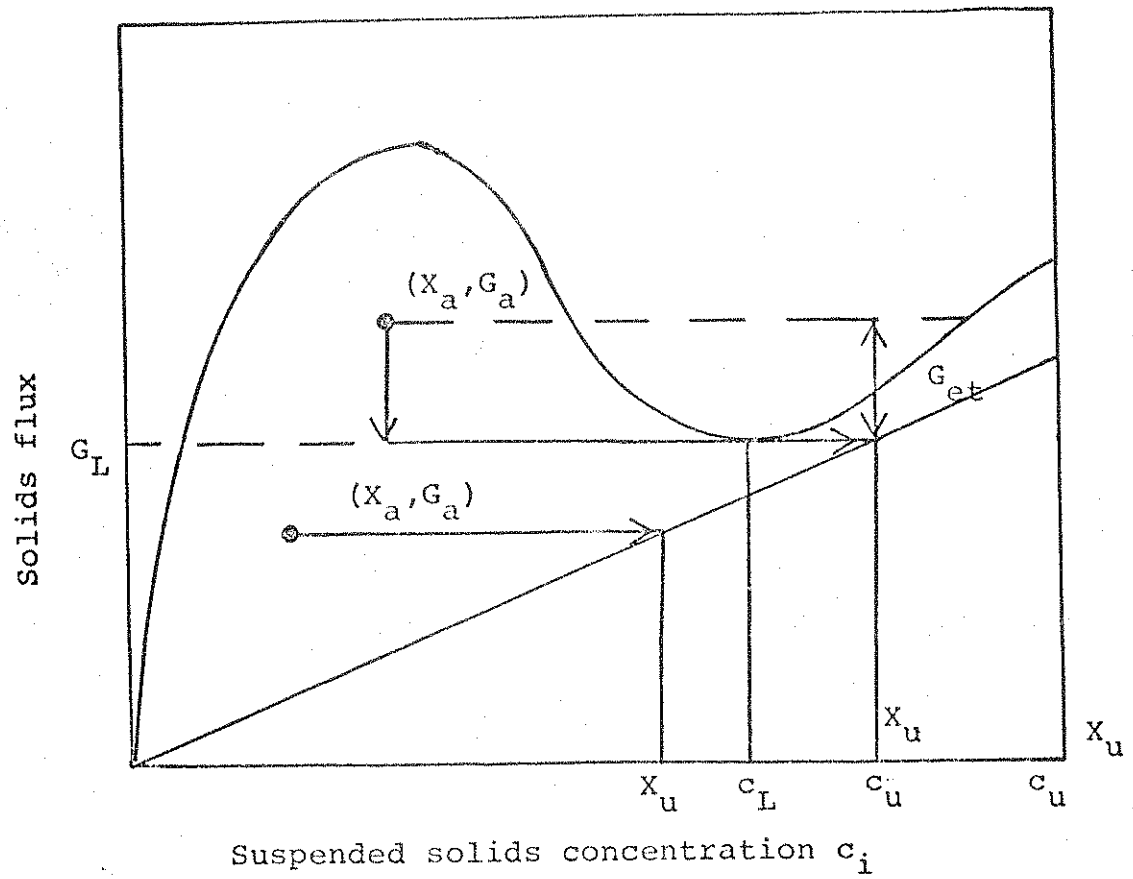


Figure 2.12 Operating points in regions I and III (23).

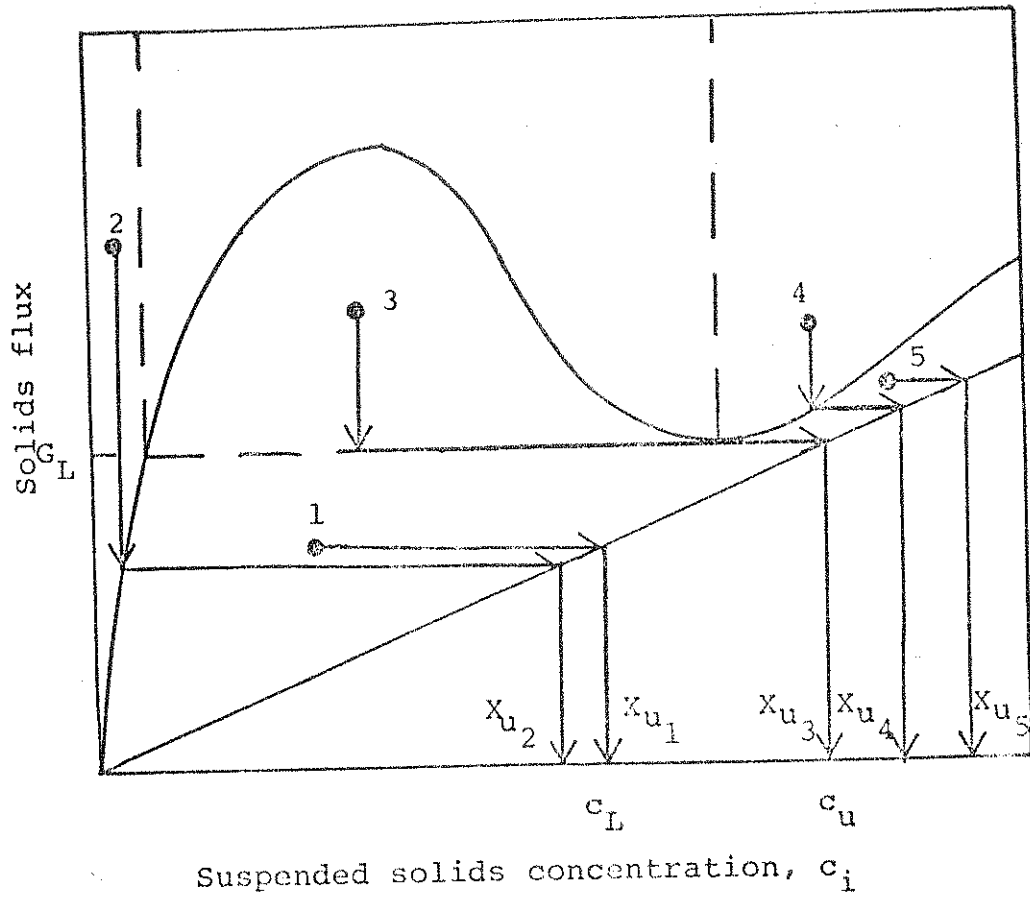


Figure 2.13 Other examples of loading conditions (23).

Table 2.7 Summary of the thickener model (23).

## Region I

If  $G_a \leq G_L$  &  $G_a \leq G_T|_{X_a}$ , then

$$X_u = G_a/u \quad \& \quad X_{et} = 0$$

## Region II

If  $X_a < c_m$  &  $G_a > G_T|_{X_a}$ , then

$$X_u = \frac{G_T|_{X_a}}{u} \quad \& \quad X_{et} = \frac{G_a - G_T|_{X_a}}{(F - F_w)/A}$$

## Region III

If  $G_a > G_L$  &  $c_m \leq X_a \leq c_L$ , then

$$X_u = c_u \quad \& \quad X_{et} = \frac{G_a - G_L}{(F - F_w)/A}$$

## Region IV

If  $X_a > c_L$  &  $G_a \geq G_T|_{X_a}$ , then

$$X_u = \frac{G_T|_{X_a}}{u} \quad \& \quad X_{et} = \frac{G_a - G_T|_{X_a}}{(F - F_w)/A}$$

Table 2.7 (cont.)

## Region V

If  $G_L < G_a < G_T|_{X_a}$  &  $X_a > c_L$ , then

$$X_u = \frac{G_a}{u} \quad \& \quad X_{et} = 0.$$

2.7 Summary

Integration of the effects of temperature with the governing equations of a CMAS has been the subject of this chapter. To evaluate the effect of temperature on the system, one must first identify the dependent variables which best reflect the performance of a CMAS. The relevant variables are the effluent quality (improvement of which is the primary function of secondary wastewater treatment), the quantity of sludge which must be disposed of (which represents a major operating cost of the system in terms of dewatering and ultimate disposal), and the power requirements for aeration (which is another operating cost). Each of these dependent variables is influenced by the effect of temperature on the bacterial growth kinetics, oxygen transfer, and sludge settling. Table 2.8 summarizes the equations necessary for calculating the dependent variables of interest, as well as related equations which reveal the interdependence of the aeration tank and the settler. Table 2.8 clearly shows that temperature influences all of the

Table 2.8 Summary of Equations

## Effluent Quality

$$S_e = S + .6(X_e) \quad (2.55)$$

$$S = \frac{(1/\theta_c + \gamma + b)K_s}{\mu_m - (1/\theta_c + \gamma + b)} \quad (2.33)$$

$$X_e = X_{ec} + X_{et} \quad (2.54)$$

$$X_{ec} = \frac{6.55X(F-F_w)}{A} \left( \frac{\mu_T}{\mu_{T_o}} \right) \quad (2.60)$$

$$\text{or } X_{ec} = \frac{382 \left( \frac{F-F_w}{A} \right)^{0.12} (FS_o/XV)^{0.27}}{X^{0.35} t} \left( \frac{\mu_T}{\mu_{T_o}} \right) \quad (2.61)$$

$X_{et}$  - See Table 2.7

$$\theta_c = \frac{VX}{F_w X_r + (F-F_w)X_e} \quad (2.29)$$

## Mass Wastage Rate

$$F_w X_r = \frac{FY_g(S_o-S)}{1+b\theta_c} - (F-F_w)X_e \quad (2.41)$$

## Power Requirements for Aeration

$$P = 0.30 Q((P_c/P_a)^{.28} - 1) \quad (2.53)$$

Table 2.8 (cont.)

$$K_L aV = K^*_q^{1-n_z} m_a \quad (2.50)$$

$$N' = K_L aV (c_m^* - c) \quad (2.47)$$

$$c^* = \frac{475 - 2.65 S_D}{33.5 + T} \quad (2.48)$$

$$c_m^* = c^* \left[ \frac{P'}{29.4} + \frac{O_t}{42} \right] \quad (2.49)$$

$$r_{O_2} V = \frac{F(S_o - S)(1 + b\theta_c^{-\beta Y_g})}{(1 + b\theta_c)} \quad (2.46)$$

dependent variables (biologically through the bacterial kinetics and physically through the settling and oxygen transfer characteristics).

Calculation of the quantities of interest is possible once the system inputs are established. The system chosen was one previously used by Roper (23), for reasons of availability and comparison. Table 2.9 lists the physical size of the system and the different operating conditions. Operational constraints are also placed on the system based on previously established physical limitations. It has been found (62) that a sludge age of less than three days causes dispersed growth among the bacteria, and they will not settle well. A sludge age in excess of fourteen days results in

Table 2.9 Physical constants and operating information

Temperature Range of Interest: 10-30 C

Volume =  $2.5 \times 10^6$  gal

Settler Area =  $14,300 \text{ ft}^2$

$S_o = 200 \text{ mg/l}$

$F_1 = 5 \times 10^6 \text{ gal/day}$

$F_2 = 9 \times 10^6 \text{ gal/day}$

Recycle Ratio,  $\alpha$

$$\alpha_1 = 0.1000$$

$$\alpha_2 = 0.1259$$

$$\alpha_3 = 0.1587$$

$$\alpha_4 = 0.2000$$

$$\alpha_5 = 0.2520$$

$$\alpha_6 = 0.3175$$

$$\alpha_7 = 0.4000$$

$$\alpha_8 = 0.5039$$

Wastage Flow Rate,  $F_w$  (MGD)

$$F_{w1} = 0.0099$$

$$F_{w2} = 0.0157$$

$$F_{w3} = 0.0250$$

$$F_{w4} = 0.0396$$

$$F_{w5} = 0.0629$$

$$F_{w6} = 0.1000$$

$$F_{w7} = 0.1587$$

$$F_{w8} = 0.2519$$

Sludge Age: 3-14 days

$$X_{et} = 0.0$$

Aeration Tank:  $800 \leq X \leq 4500$

pin floc, which also does not settle well. So for adequate settling, the sludge age should lie between 3 and 14 days. Other restrictions are that, in normal operation, there are no suspended solids lost to the effluent due to thickener failure and that the concentration of cells in the aeration tank lies between 800 and 4500 mg/l. Restrictions are placed on the cell concentration to allow adequate volume for oxygen transfer and to provide for adequate thickening and clarification.

Control of a CMAS can be maintained through use of the sludge age,  $\theta_c$ . The sludge age is a measure of the growth condition of the microorganism. As such, it relates not only to the sludge settling characteristics, but more importantly it governs the quality of the plant effluent. Controlling on the basis of sludge age provides the most rational means of achieving stable effluent quality. Therefore, the sludge age provides a valid controlling parameter for assessing the effect of temperature on the CMAS.

Calculations were performed for the two influent flows and for temperatures in the range 10-30 C, at 5 C increments, which provides 320 different operational points (corresponding to the ranges of  $\alpha$  and  $F_w$ ) for each influent flow rate. The computer solution allows calculation of the output parameters as functions of sludge age and temperature, and determines if the plant has met the previously defined operational limitations. With this information the effect of temperature on the normal operation of a secondary



wastewater treatment plant can be evaluated to provide insight on what happens in a CMAS as the temperature changes and to determine an optimum operating temperature.

## CHAPTER 3 SIMULATION RESULTS AND DISCUSSION

### 3.1 Introduction

In this chapter, the results for the temperature dependent CMAS are presented. Two sets of results are presented, corresponding to the two different clarification models. Recall that these models predict significantly different results for the concentration of suspended solids in the effluent. In the model of Tarrer (52), the concentration of suspended solids in the effluent has been found to be directly proportional to the concentration of cells in the aeration tank, while in the model of Agnew (48), an inverse proportionality has been found. The operator of a particular plant would have to determine which suspended solids model is applicable for the treatment facility.

The important parameters which could be used to establish the effect of temperature on the operation of a wastewater treatment plant are the effluent quality, the amount of sludge which must be disposed of (the mass wastage rate), and the power requirements for aeration. The last two parameters, mass wastage rate and power requirements reflect the two major operating costs of the system. They are determined as a function of temperature and the sludge age or

mean cell residence time,  $\theta_c$ . The overall system performance is determined by the sludge age, which is the ratio of the total amount of solids in the aeration tank to the rate at which solids are withdrawn from the system. The sludge age may be effectively utilized for process control, as it governs the quality of the plant effluent and is related to the sludge settling characteristics. Therefore, by varying the sludge age, the effluent quality from the plant is also varied.

The calculations which follow are based on an influent soluble substrate concentration of 200 mg/l and influent flow rates of 5 MGD and 9 MGD.

### 3.2 Discussion of the Model Using the Tarrer Settling Expression

In the Tarrer clarification model, the concentration of suspended solids in the effluent is directly proportional to the concentration of cells in the aeration tank

$$X_{ec} = 6.555X[(F - F_w)/A] \frac{\mu_T}{\mu_{T_O}} \quad (2.60)$$

Figures 3.1 and 3.2 indicate that the amount of suspended solids in the effluent increases with increasing sludge age and decreasing temperature. The reason for these trends may be seen from the following expression

$$X = \frac{Y_g (S_o - S)}{(1/\theta_c + b) \bar{t}} \quad (2.39)$$

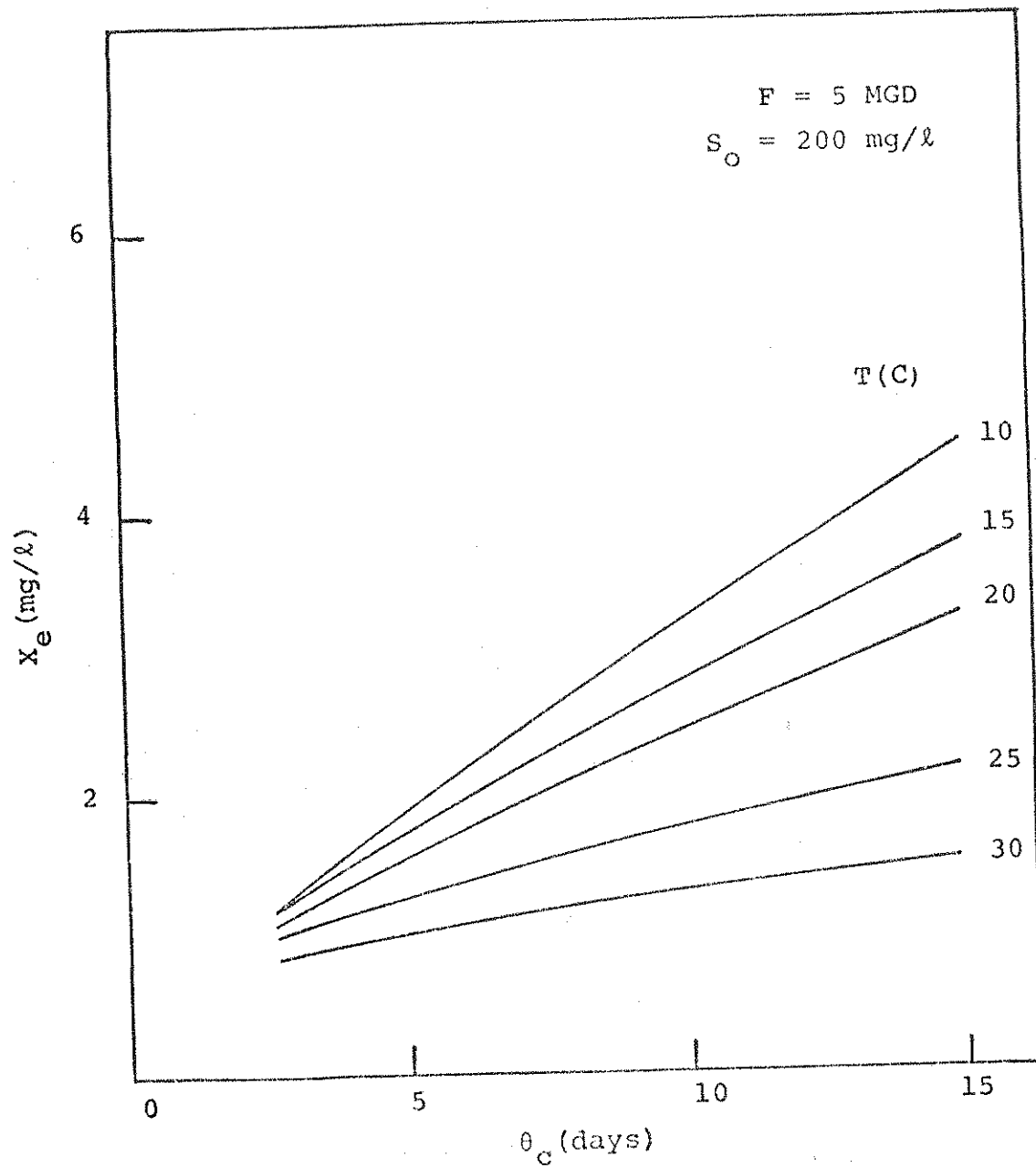


Figure 3.1 Suspended solids in effluent for the Tarrar settling model.

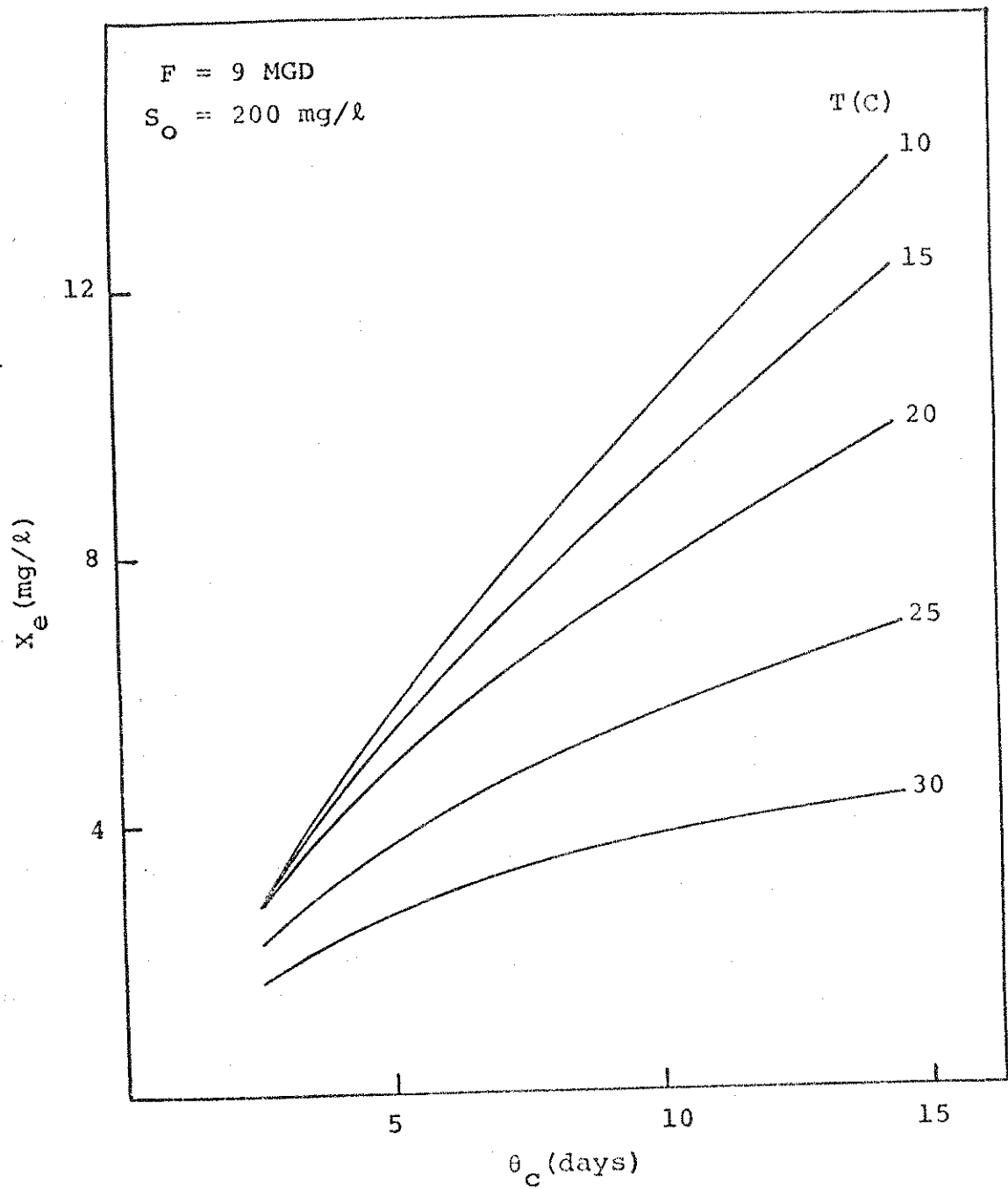


Figure 3.2 Suspended solids in the effluent for the Tarrer settling model.

As  $\theta_c$  increases,  $X$  must do likewise, thereby providing for increased cell concentration in the aeration tank. As the flow increases, the hydraulic residence time,  $\bar{t}$ , decreases, thereby increasing the cell concentration. As the temperature increases for the range  $T \leq 20^\circ\text{C}$ , both  $Y_g$  and  $b$  increase, causing the cell concentration to remain relatively constant. However, for the range  $T > 20^\circ\text{C}$ ,  $Y_g$  decreases while  $b$  continues to increase, causing the cell concentration in the aeration tank to decrease. Hence the decrease in suspended solids in the effluent for  $T \leq 20^\circ\text{C}$  is due solely to the decrease in the water viscosity as the temperature increases from  $10^\circ\text{C}$ , while for  $T > 20^\circ\text{C}$  the decrease is due to the combined effect of decreasing water viscosity and decreasing concentration of suspended solids in the aeration tank.

The total effluent quality is given by

$$S_e = S + 0.6(X_e) \quad (2.55)$$

which applies for normal plant operation (no thickener failure). The soluble substrate concentration is independent of the influent flow rate and substrate concentration and is controlled through variation in the sludge age for a given temperature

$$S = \frac{(1/\theta_c + \gamma + b)K_s}{\mu_m - (1/\theta_c + \gamma + b)} \quad (2.33)$$

As the sludge age increases,  $S$  decreases (Figure 3.3). The temperature dependent parameters in this expression are  $\mu_m$  and  $b$ , both of which increase with increasing temperature. For a given sludge age, as the temperature increases,  $S$  decreases due to the larger effect of temperature on  $\mu_m$  than on  $b$ .

Figures 3.4 and 3.5 illustrate the effect of sludge age on the total effluent quality. Although the soluble substrate concentration decreases with increased sludge age, the attendant increase in effluent suspended solids offsets this effect. Hence plant operation may become poorer at extended sludge ages. At the increased flow rate of 9 MGD, the effluent quality actually deteriorates with increased sludge age. This is due to an increase in  $X$ , the suspended solids concentration in the aeration tank (equation 2.39), and an increase in the overflow rate  $(F-F_w)/A$  which combine to increase suspended solids loss. At the lower flow rate of 5 MGD the effect is not as obvious, but the best total effluent quality is obtained for sludge ages between 7 and 10 days.

The effect of temperature on total effluent quality is given in Figure 3.6 and 3.7. These results clarify the idea that, as the temperature increases, the effluent quality will also increase. This trend is a consequence of the fact that both the soluble substrate and suspended solids concentration in the effluent decrease with increasing temperature.

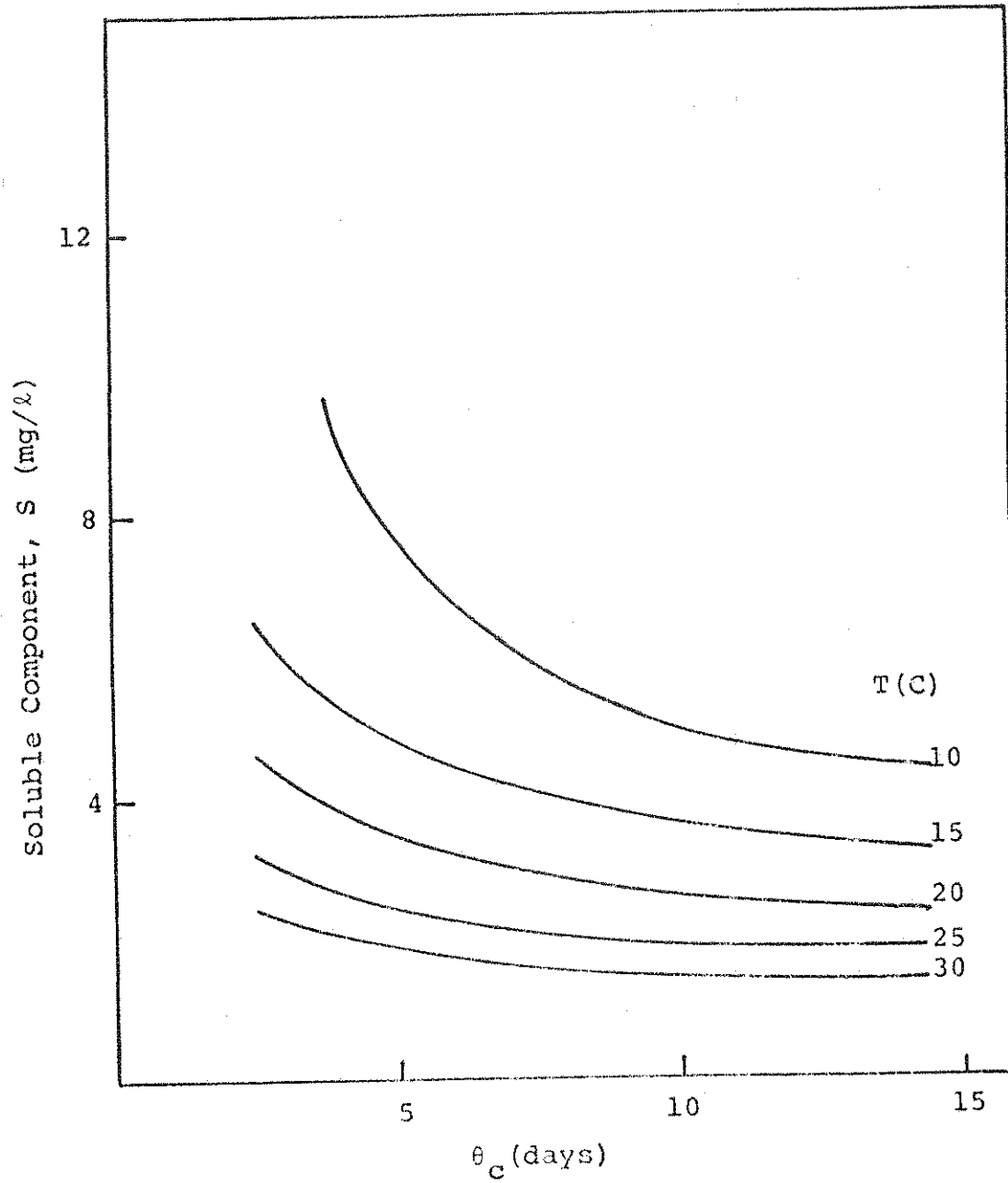


Figure 3.3 Effect of sludge age on soluble component of effluent quality.



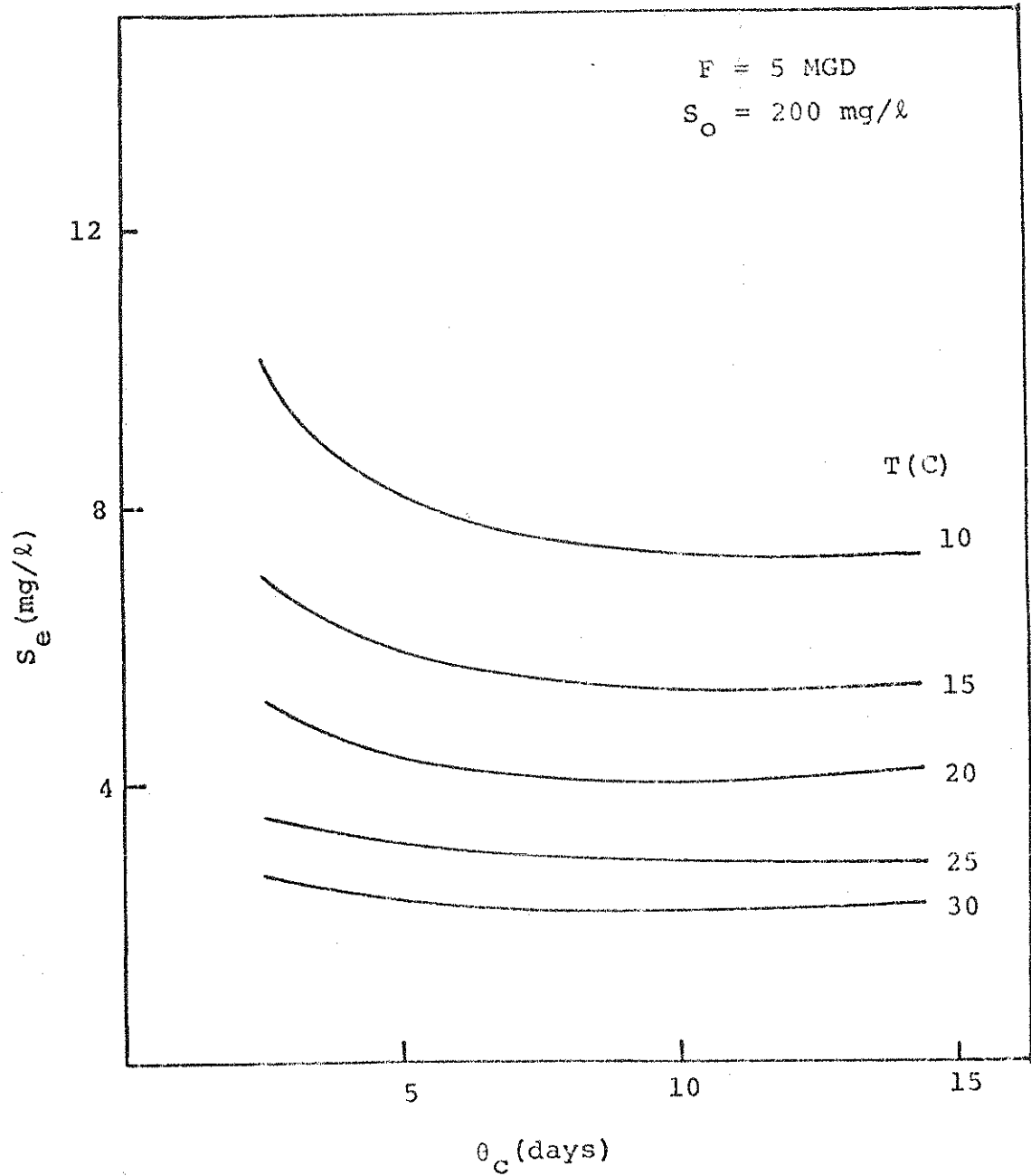


Figure 3.4 Effect of sludge age on total effluent quality for the Tarrar settling model

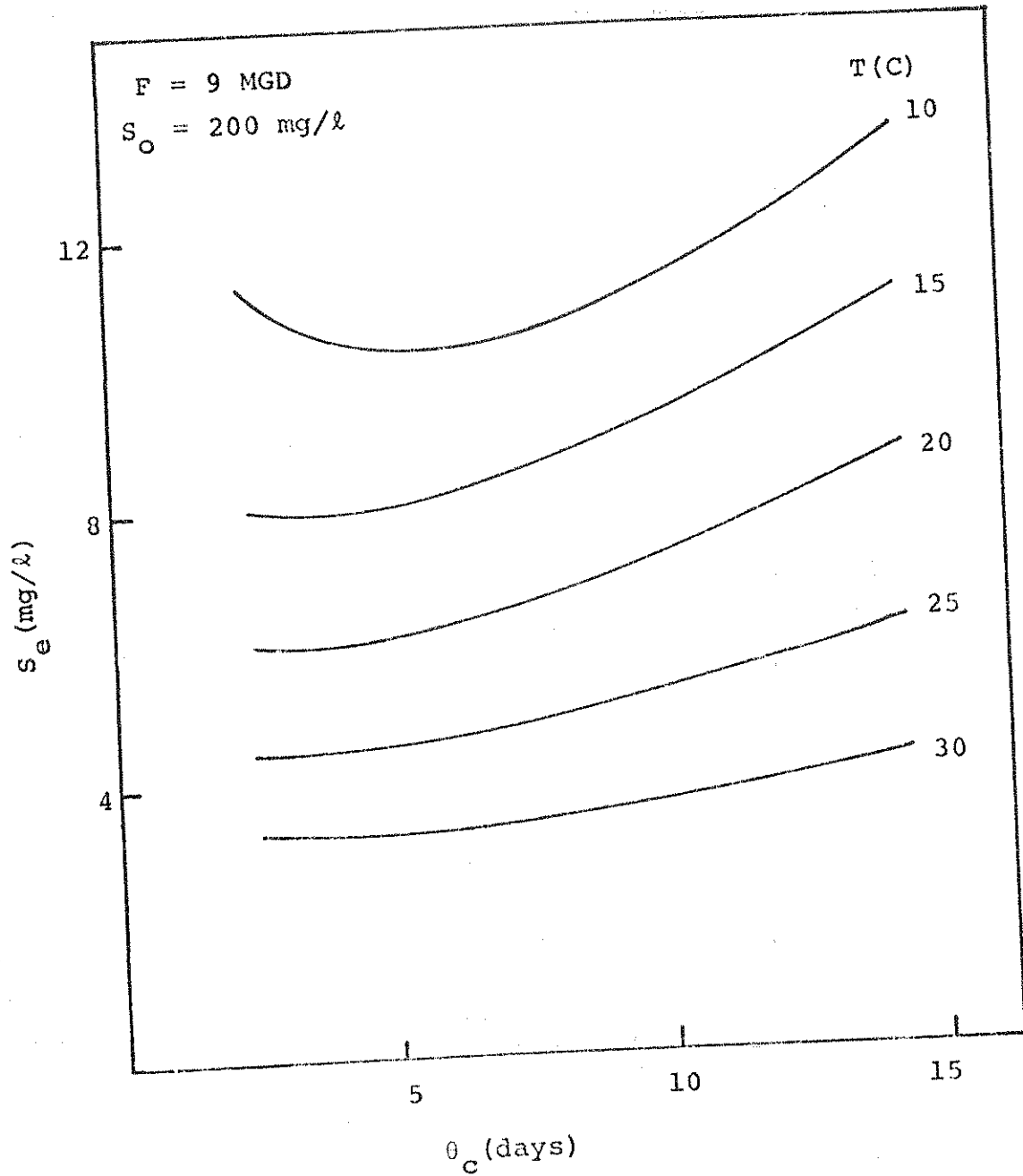


Figure 3.5 Effect of sludge age on total effluent quality for the Tarrar settling model.

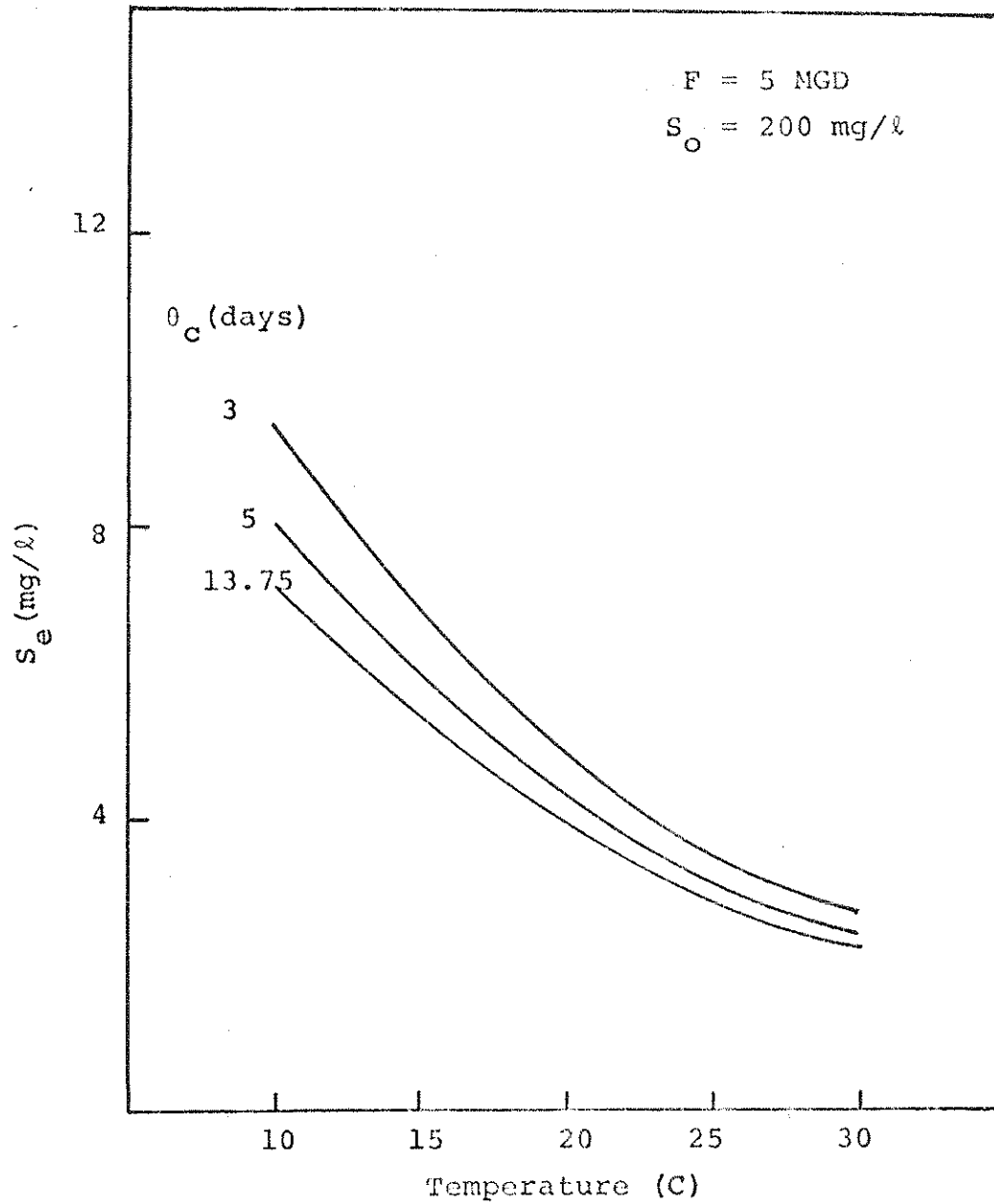


Figure 3.6 Effect of temperature on total effluent quality for the Tarrar settling model.

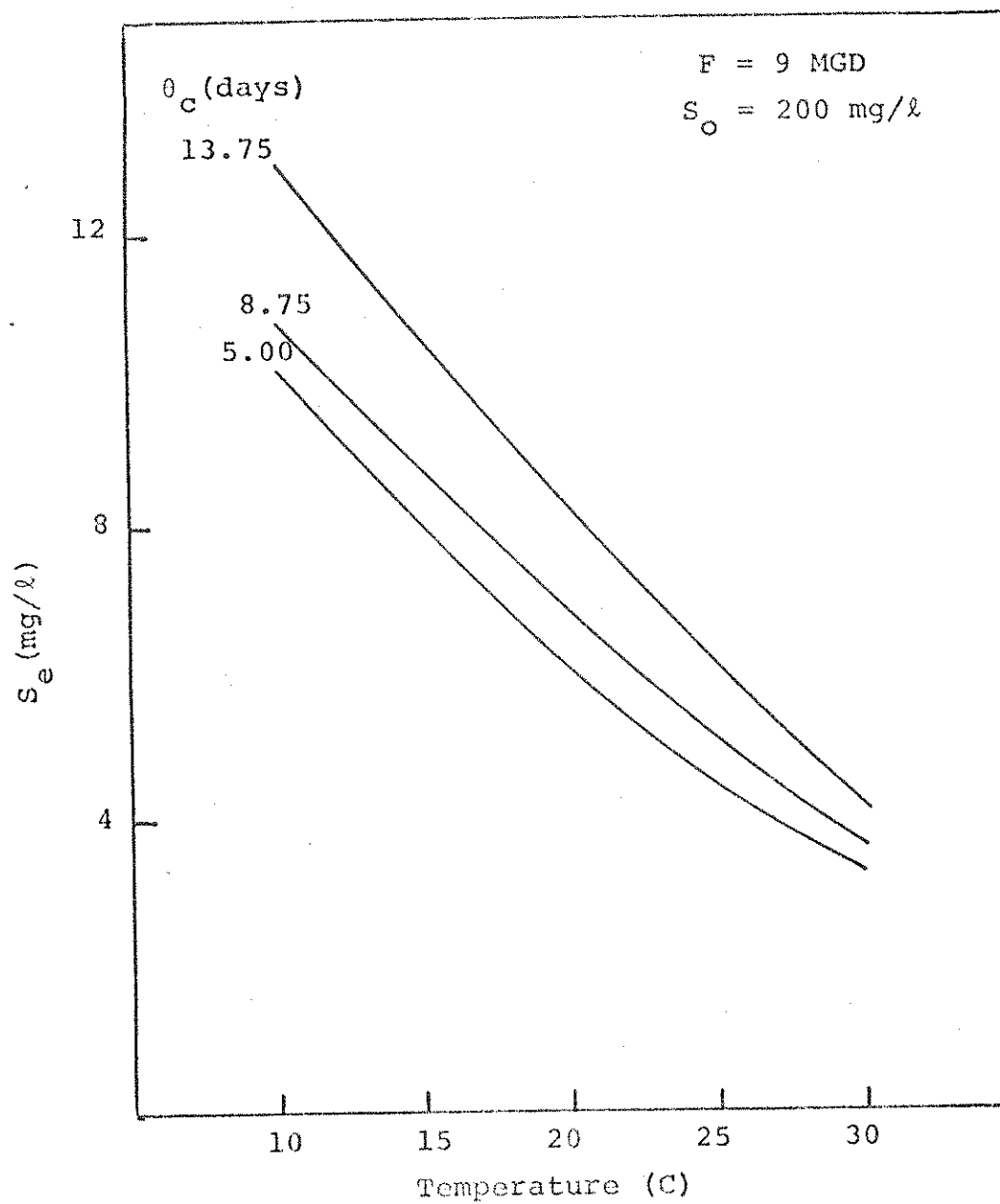


Figure 3.7 Effect of temperature on total effluent quality for the Tarror settling model.

However, in Figure 3.6 total effluent quality improves with increasing sludge age, while in Figure 3.7 it decreases with increasing sludge age. Figure 3.7 reflects the increased rate of solids loss over the settler at the increased flow of 9 MGD. As the sludge age increases, the amount of solids lost over the settler also increases, producing the reversed trend of Figure 3.7.

One of the major operating costs of a waste treatment system relates to the disposal of the excess microorganisms (sludge) produced. The excess sludge must be dewatered and then disposed of by incineration, land fill or alternative methods. The requirements of handling large volumes of sludge contribute to the large cost of sludge disposal. The net rate at which sludge is produced is given by

$$F_w X_r = \frac{F Y_g (S_o - S)}{1 + b\theta_c} - (F - F_w) X_e \quad (2.41)$$

The first term on the right-hand side of this equation represents the rate at which the biosystem is producing cells, and is given the symbol  $P_x$ . This is the gross rate of sludge production. The second term represents the rate at which cells are lost over the settler. Collectively, these terms provide a measure of the effect of settler performance on the amount of sludge which must be disposed of.

Figures 3.8 and 3.9 show the gross rate at which the biosystem is producing cells,  $P_x$ . The increased flow rate of

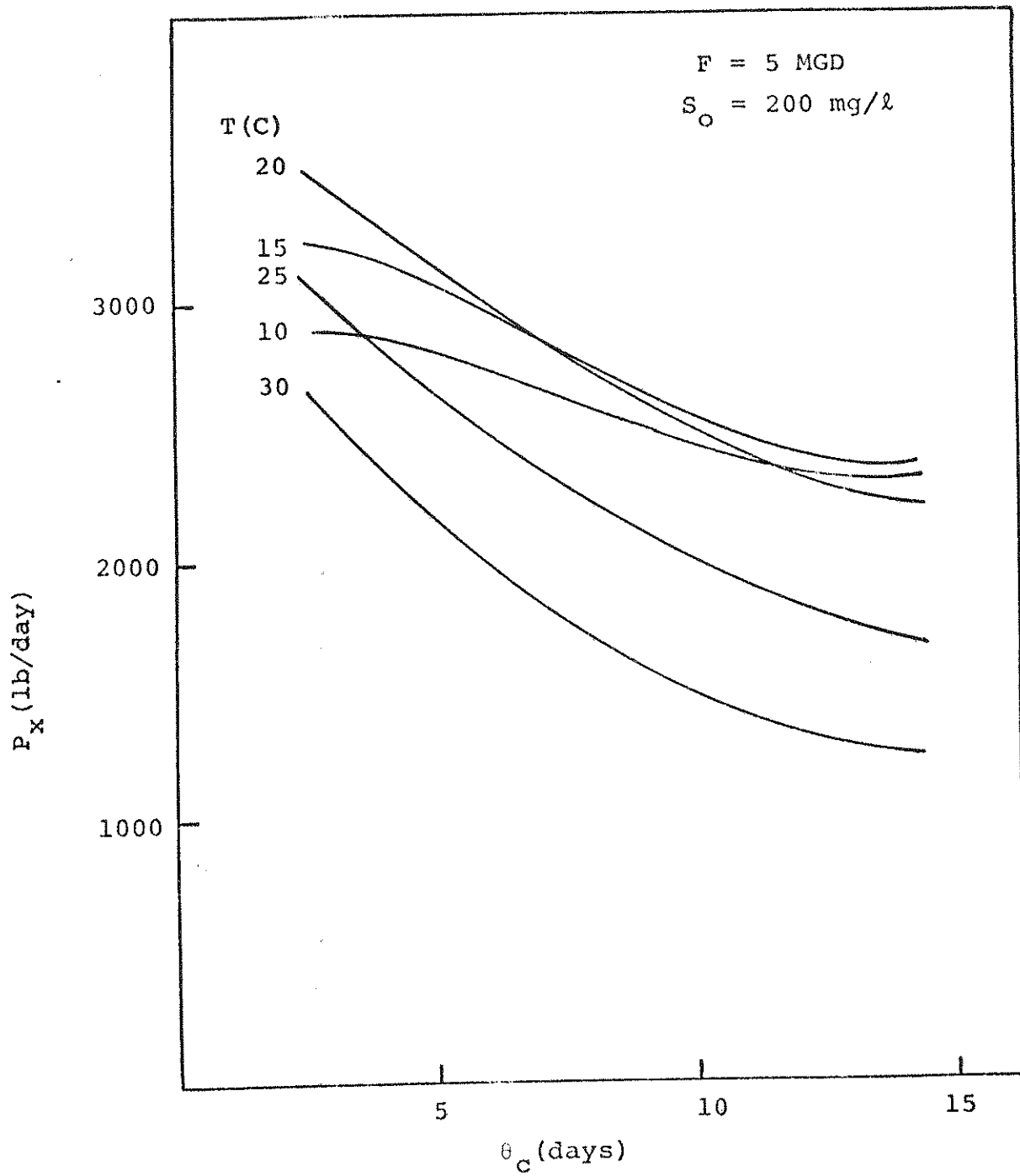


Figure 3.8 Gross production of sludge.

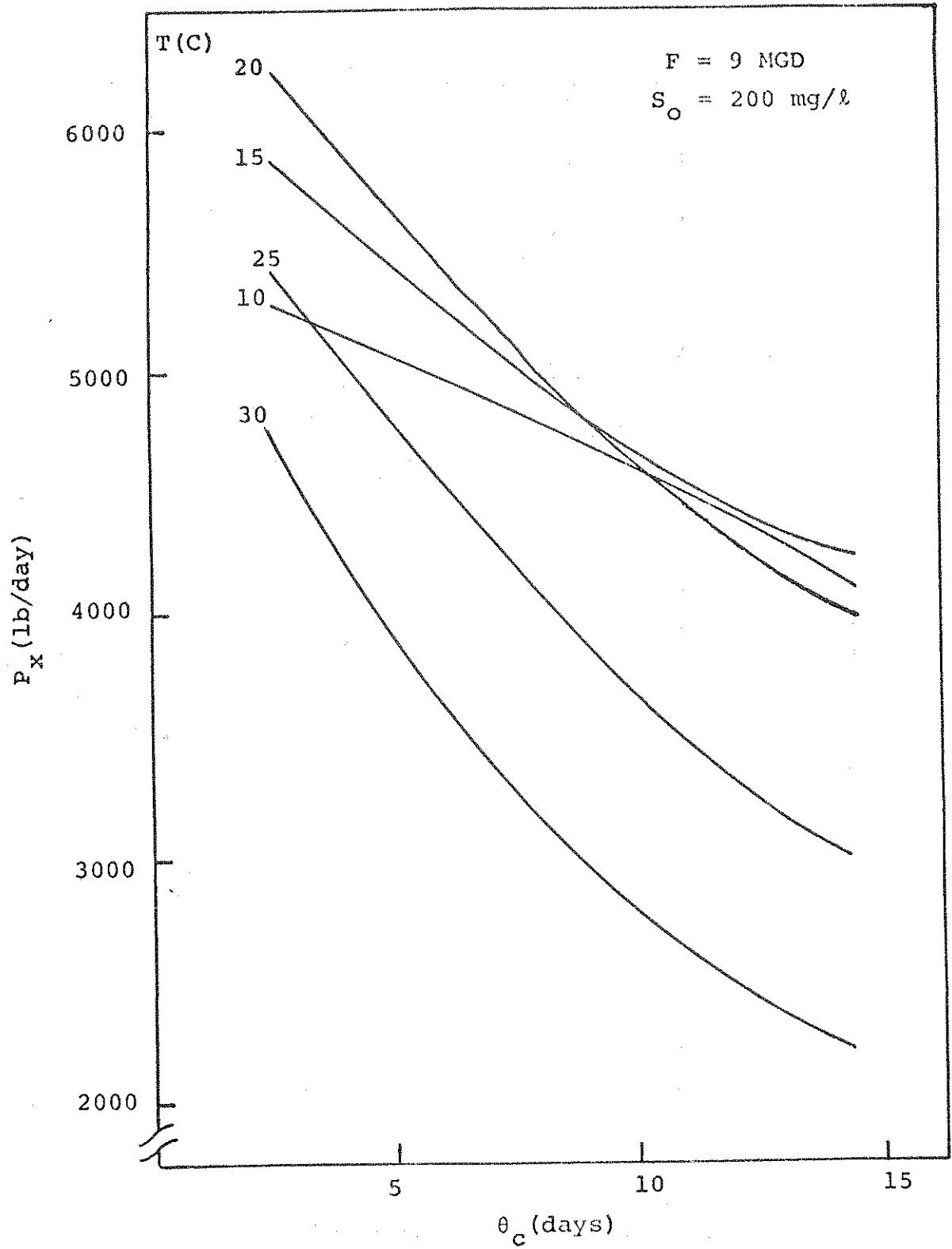


Figure 3.9 Gross production of sludge.

9 MGD results in the increased rate of gross sludge production. The increased effect of decay results in the decrease in the gross production of sludge as the sludge age increases.

Figures 3.10 and 3.11 indicate the rate at which solids are lost over the final settler,  $(F-F_w)X_e$ . The results of Figures 3.8 and 3.10, as well as those of Figures 3.9 and 3.11, may be combined to obtain the net wastage rate shown in Figures 3.12 and 3.13. Because the amount of solids which are lost over the final settler increases with increasing sludge age, the amount by which the net mass wastage rate is less than the rate at which the biosystem produces cells must also increase with increasing sludge ages.

The effect of temperature on the gross production of sludge can be seen in Figures 3.14 and 3.15. The gross rate at which the biosystem produces sludge decreases rapidly from 20 C due to the effect of temperature on  $Y_g$ , the true growth yield, which decreases as the temperature increases from 20 C. At lower temperatures (<20 C), this effect has to be combined with that of the sludge age and the effect of temperature on the decay constant. At short sludge ages, the effect of decay is small, so the gross production of sludge follows the same trends as  $Y_g$ , increasing until 20 C and then decreasing. For longer sludge ages (>8 days) the effect of decay is more pronounced. The coefficient  $b$  increases with increasing temperature, so at long sludge ages the two effects are competing which provides for the relatively constant gross production of sludge up to 20 C.



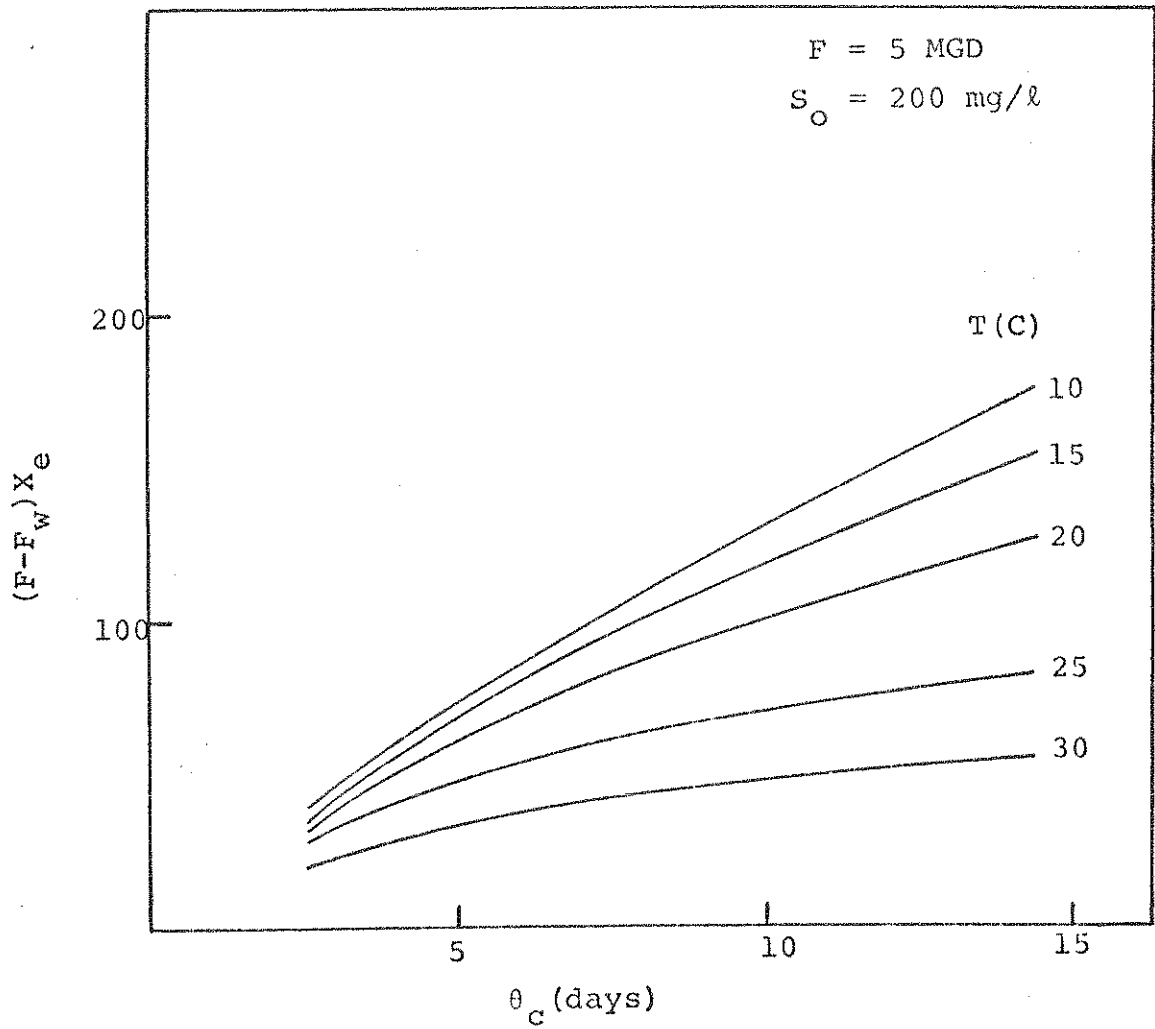


Figure 3.10 Effect of sludge age on rate of solids loss over the final settler for the Tarrar settling model.

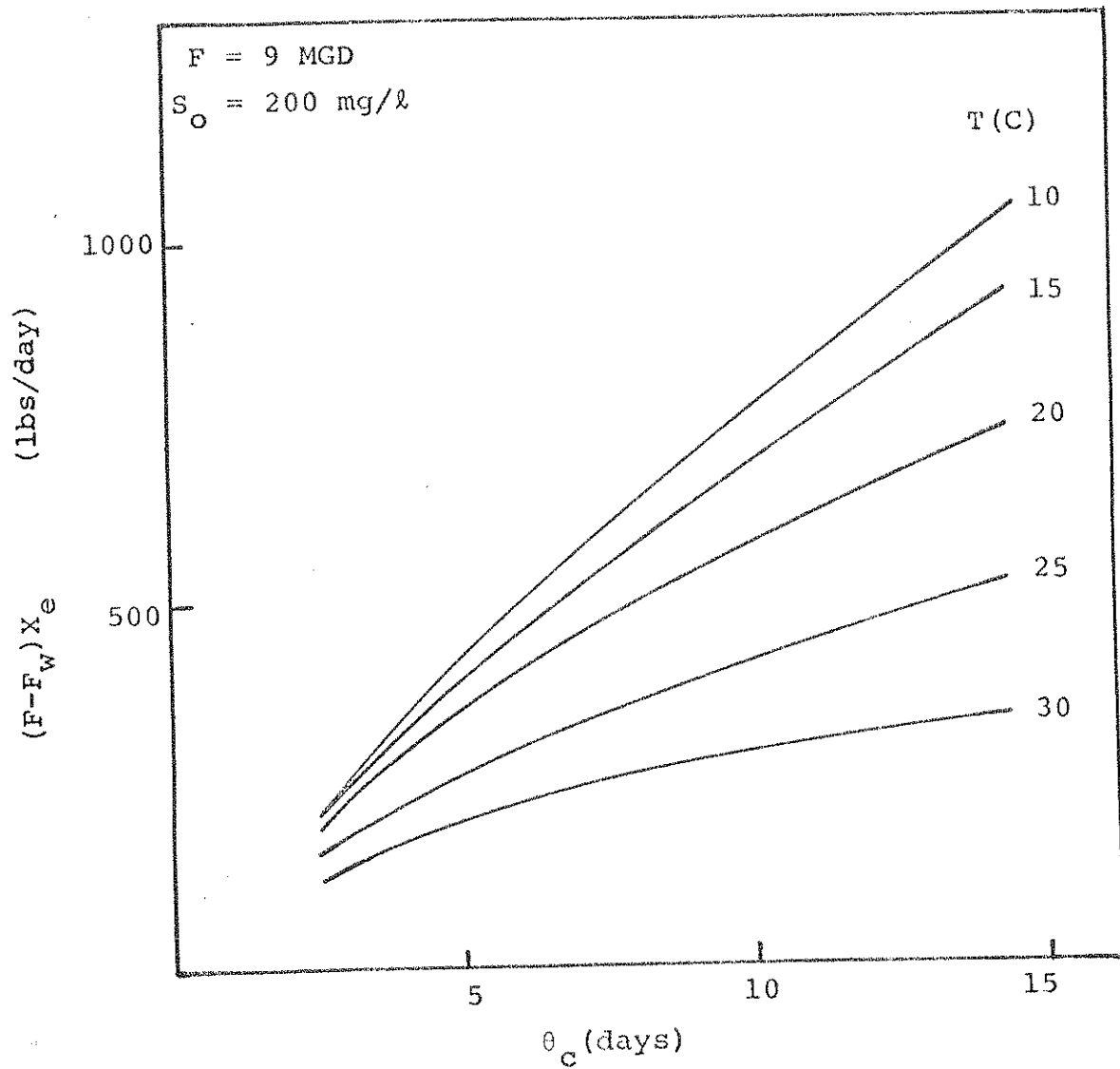


Figure 3.11 Effect of sludge age on rate of solids loss over final settler for Tarrar settling model.

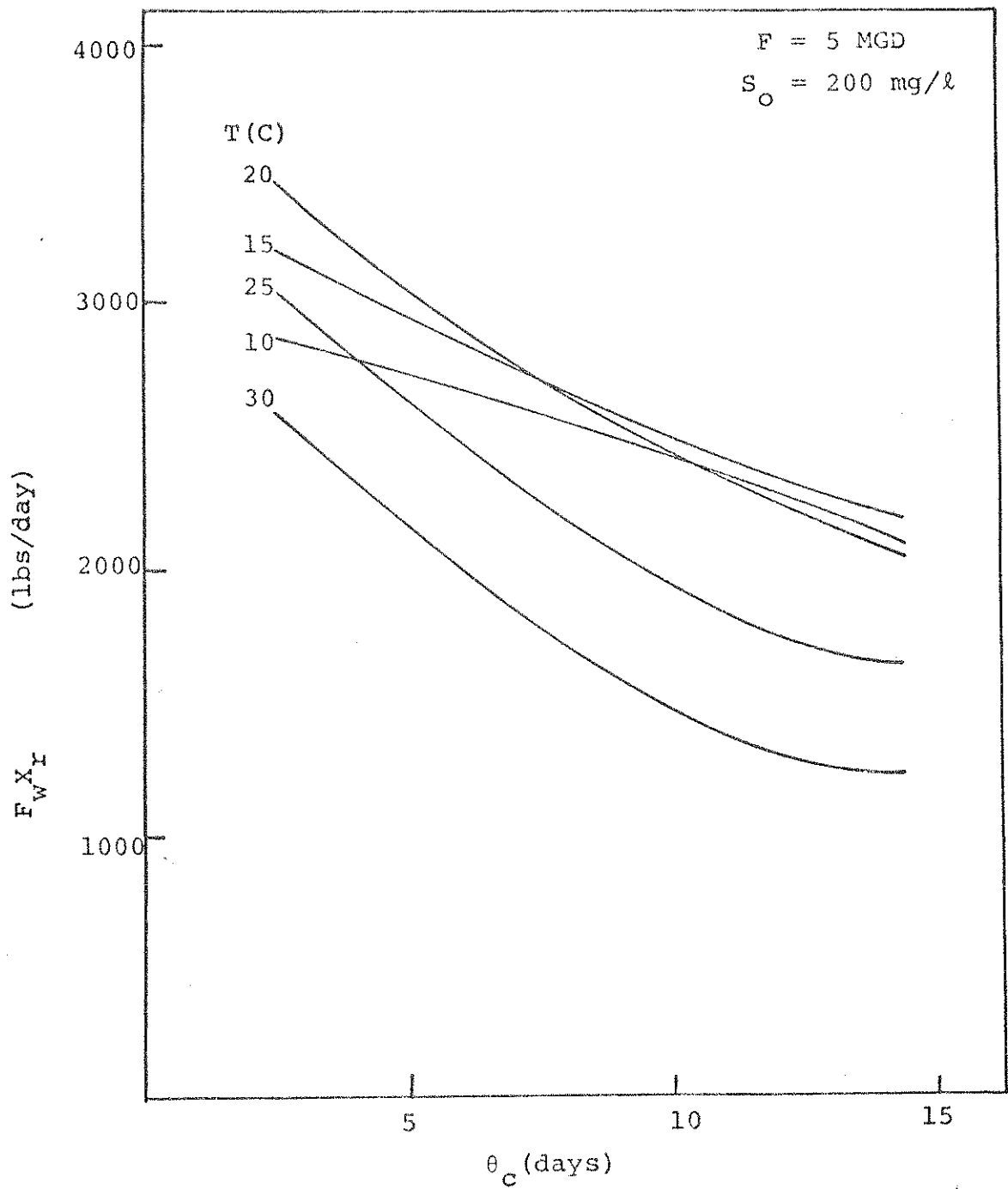


Figure 3.12 Effect of sludge age on net mass wastage rate for the Tarrar settling model.

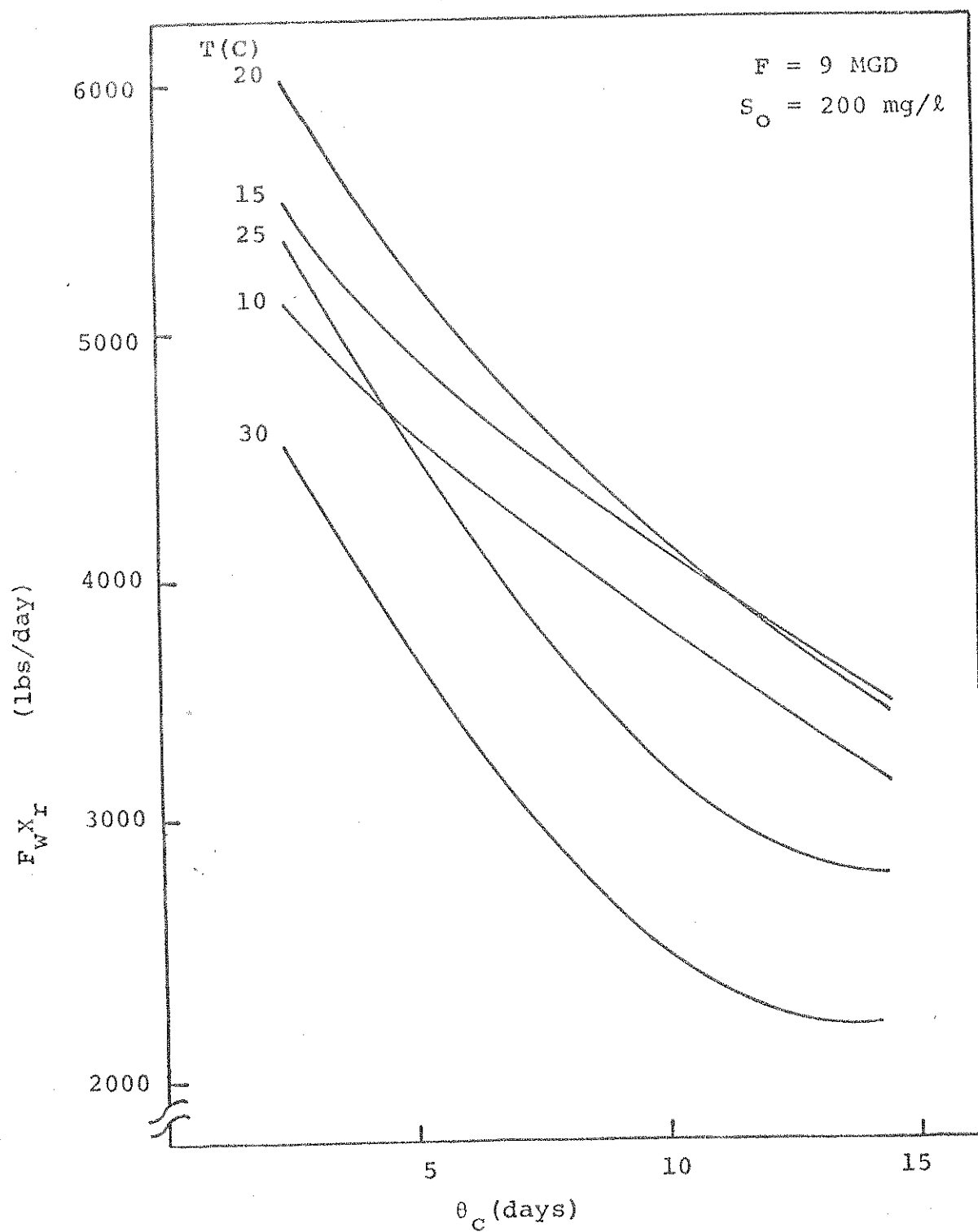


Figure 3.13 Effect of sludge age on net mass wastage rate for the Tarrer settling model.

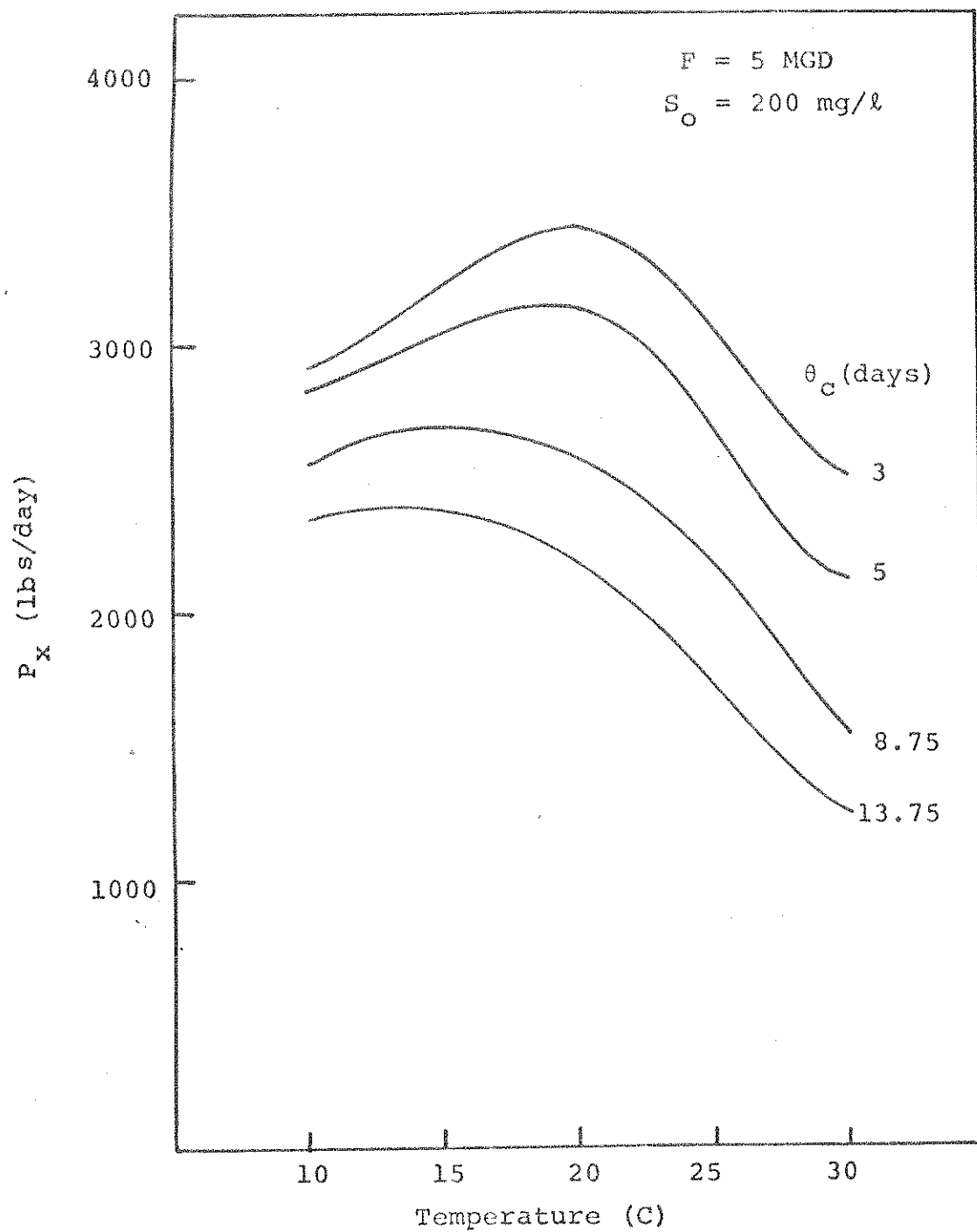


Figure 3.14 Effect of temperature on gross production of sludge.

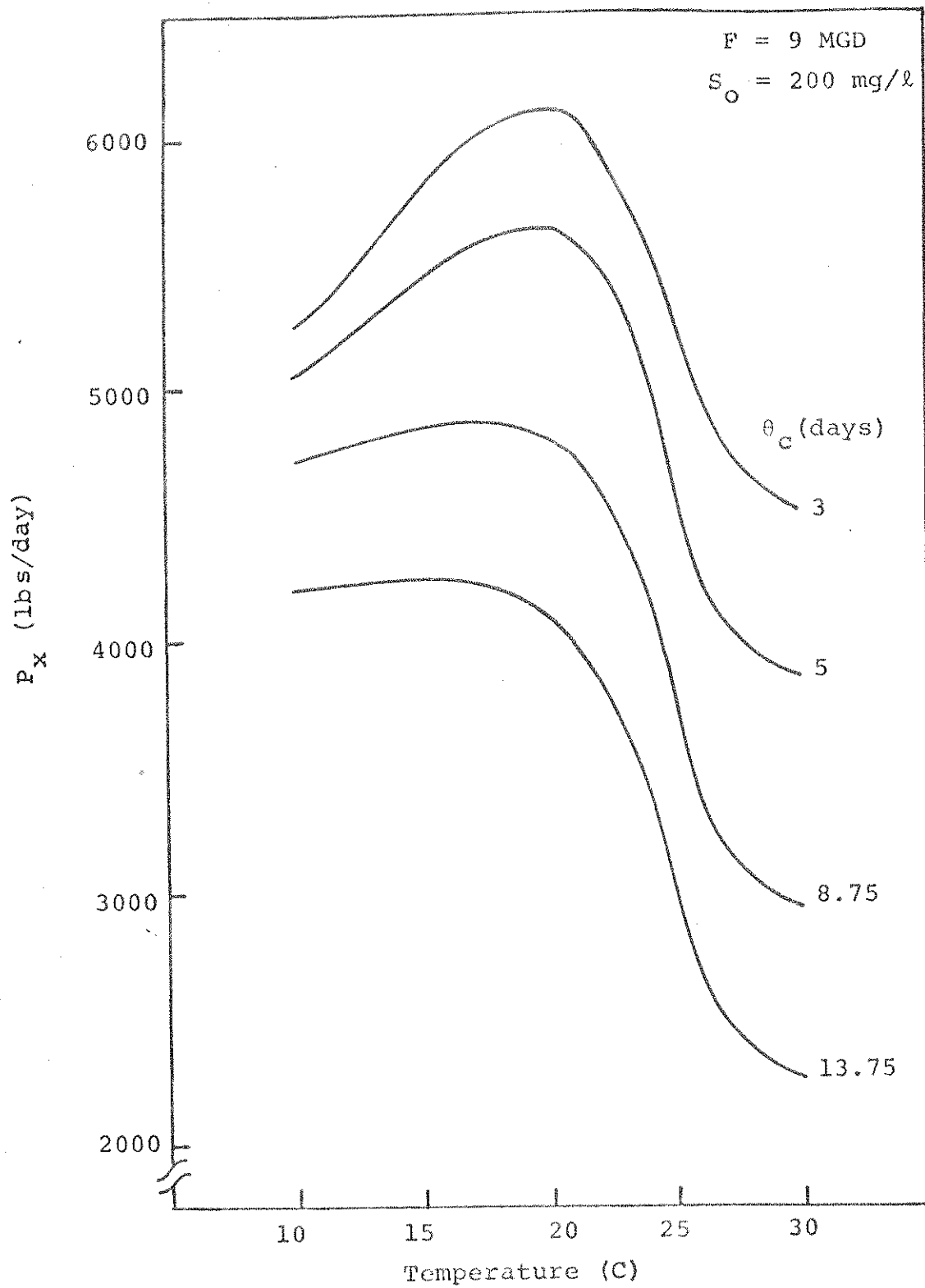


Figure 3.15 Effect of temperature on gross production of sludge.

The temperature effects on the net mass wastage rate are shown in Figures 3.16 and 3.17. The effect of temperature on solids lost over the final settler,  $(F-F_w)X_e$ , is to decrease the rate of solids loss (Figures 3.10 and 3.11). Therefore the effect of temperature is to increase the net mass wastage rate as the temperature increases, over what it would be for a constant temperature.

High temperatures ( $>20$  C) obviously reduce the amount of sludge which must be disposed of. Extended sludge ages also reduce the net mass wastage rate. Increasing temperature improves the total effluent quality for any temperature increase. However, although the effluent quality deteriorates for increasing sludge age, the effect of temperature on improving the effluent quality would allow for operation at extended sludge ages. This would give minimal sludge production and a good quality effluent for temperatures greater than 20 C.

The power requirements for aeration are a complex function of the bacterial oxygen demand, the solubility of oxygen in water, and the volumetric mass transfer coefficient  $K_L a$ . The oxygen requirement for the bacteria is given by

$$r_{O_2}^V = \frac{F(S_o - S)(1 + b\theta_c - \beta Y_g)}{(1 + b\theta_c)} \quad (2.46)$$

For a given sludge age, the oxygen demand increases for temperatures greater than 20 C due to the effect of

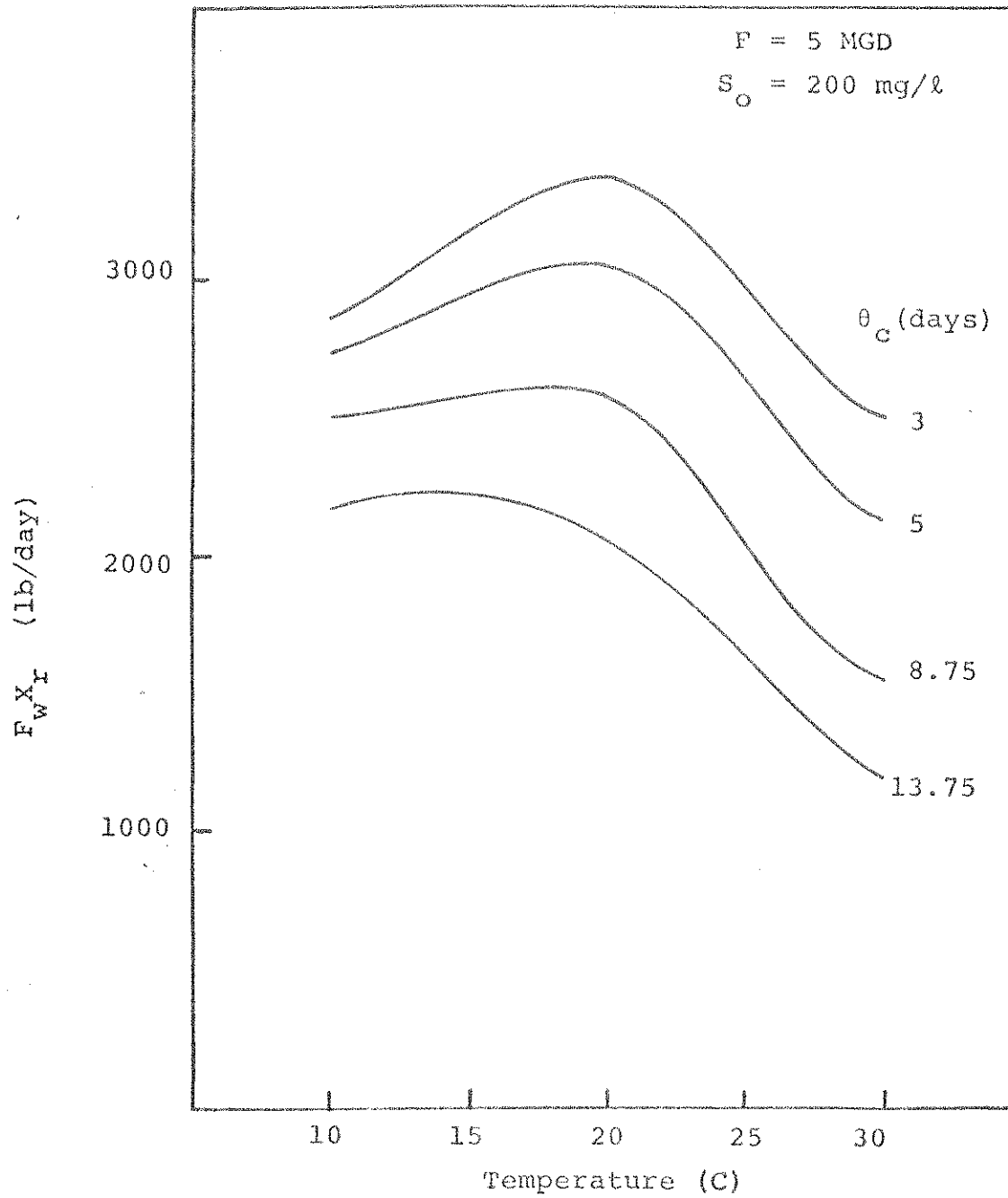


Figure 3.16 Effect of temperature on net mass wastage rate for the Tarrar settling model.



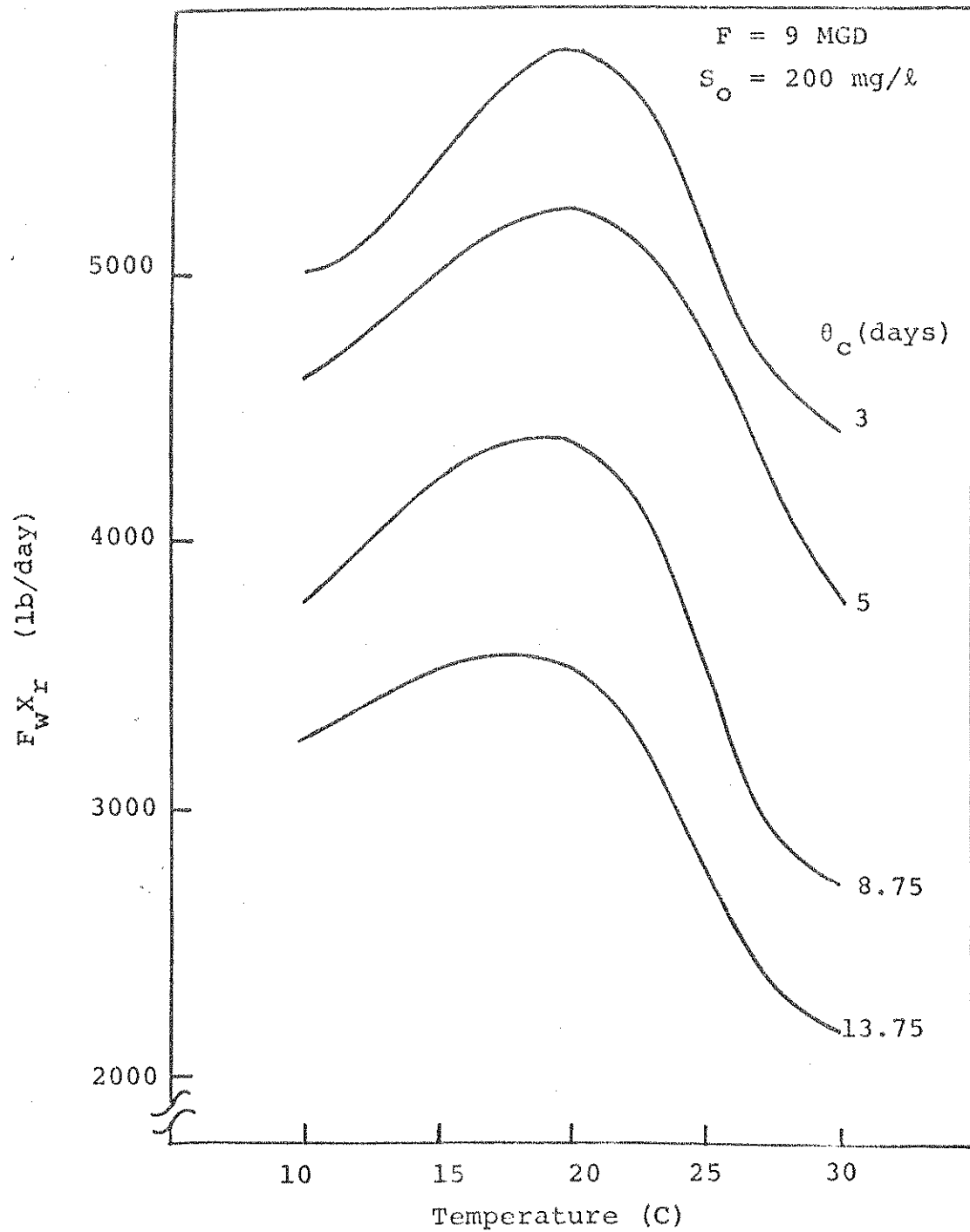


Figure 3.17 Effect of temperature on net mass wastage rate for the Tarrer settling model.

temperature on  $Y_g$ . For temperatures less than 20 C, the sludge age and effect of temperature on  $b$ , the decay constant, must be included. For short sludge ages (<5 days), the effect of cell decay does not play a large role, so the oxygen demand decreases from 10 to 20 C. At longer sludge ages, the effect of cell decay becomes important, and the fact that  $b$  is increasing with temperature serves to make the oxygen demand fairly constant with the temperature increase from 10 to 20 C.

The power required for aeration is directly proportional to the required air flow rate  $Q$

$$P = 0.30Q[(P_c/P_a)^{0.28} - 1] \quad (2.53)$$

which in turn is related to the oxygen demand of the bacteria and to the solubility of oxygen in water, equations (2.46), (2.47), (2.48), (2.50) and (2.52). The solubility of oxygen in water decreases with increasing temperature. The system constant,  $K^*$  (equation (2.52)), decreases with increasing temperature, but not enough to offset the effect of increasing temperature on oxygen demand and oxygen solubility. The cumulative effects of temperature on the power requirements is shown in Figures 3.18 and 3.19. The power requirements increase from 20 C. The effect from 10-20 C is dependent upon the sludge age. The longer sludge ages increase the effect of cell decay on the oxygen demand.

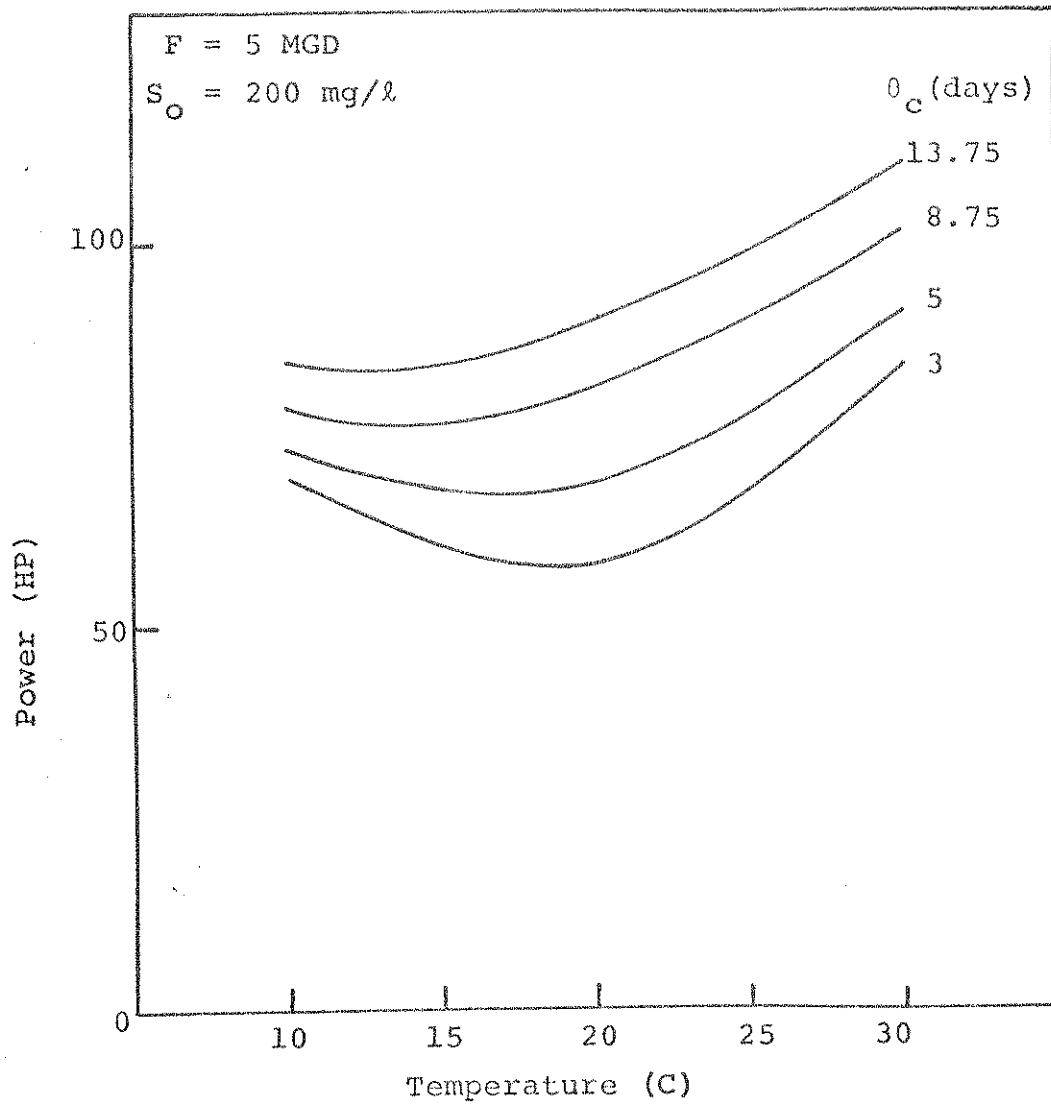


Figure 3.18 Effect of temperature on power requirements for aeration.

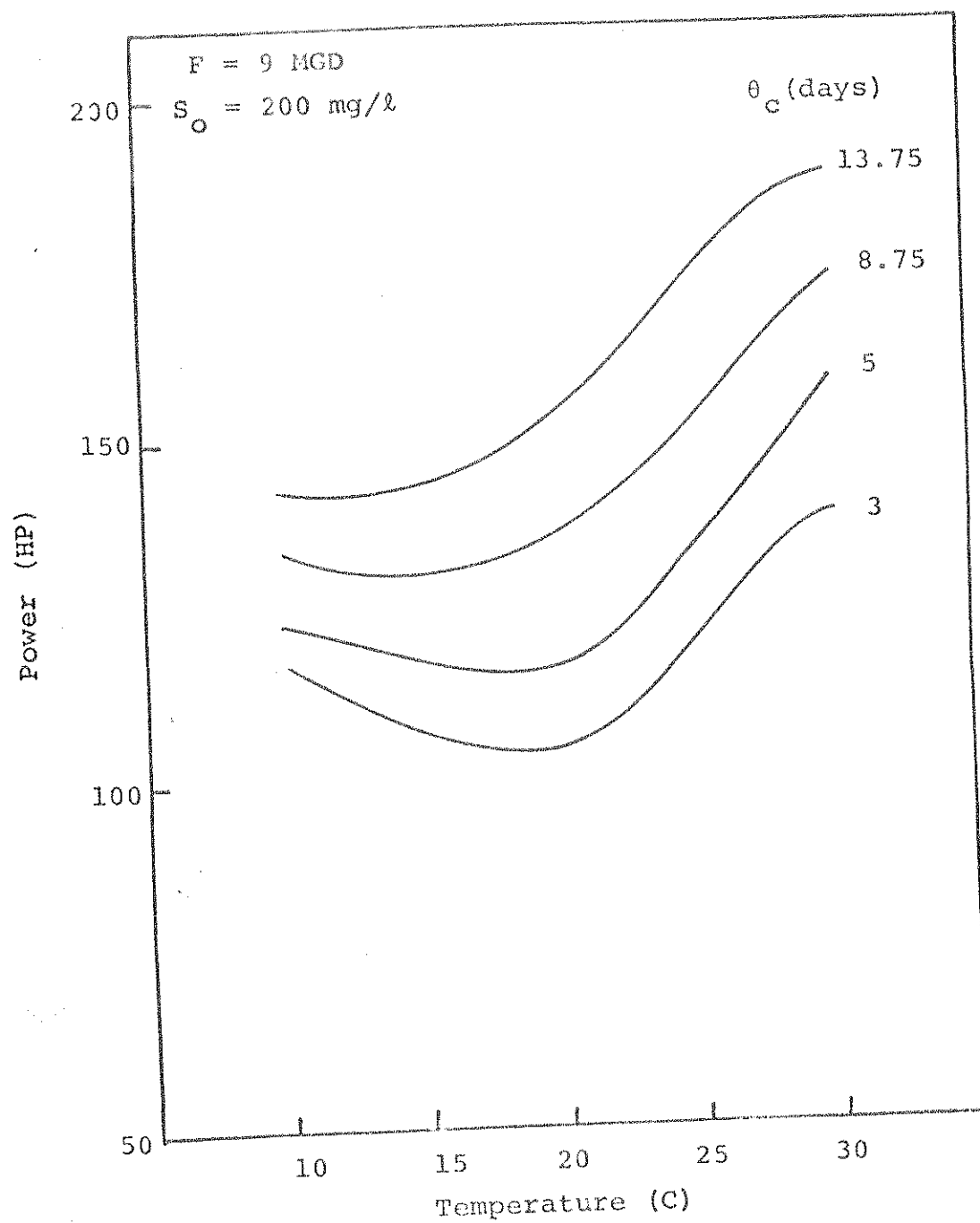


Figure 3.19 Effect of temperature on power requirements for aeration.

Figures 3.20 and 3.21 illustrate the effect of sludge age on the power requirements. As the sludge age increases, the power requirements for aeration do likewise. This is due to the increasing effect of cell decay with increasing sludge age.

In summary, the Tarrer clarification model predicts an increased concentration of suspended solids in the effluent with increasing sludge age, due to an increased concentration of suspended solids in the aeration tank. Temperature affects the suspended solids loss through changes in the water viscosity and the effect of temperature on the cell concentration in the aeration tank. The effluent quality improves for any increase in temperature, due to improved settling of suspended solids and soluble substrate removal. The total effluent quality decreases with increasing sludge age for the high range of influent flow rates ( $F \sim 9$  MGD). However, at low influent flow rates effluent quality will still improve with increasing sludge age. The net mass wastage rate decreases rapidly as the temperature increases above 20 C. Depending on the sludge age, for temperatures less than 20 C, the net mass wastage rate will either increase with increasing temperature to 20 C or remain approximately constant. The net mass wastage rate decreases with increasing sludge age, due to both the increased effect of cell decay on the biosystem and the increased amount of solids lost over the final settler. The power requirements

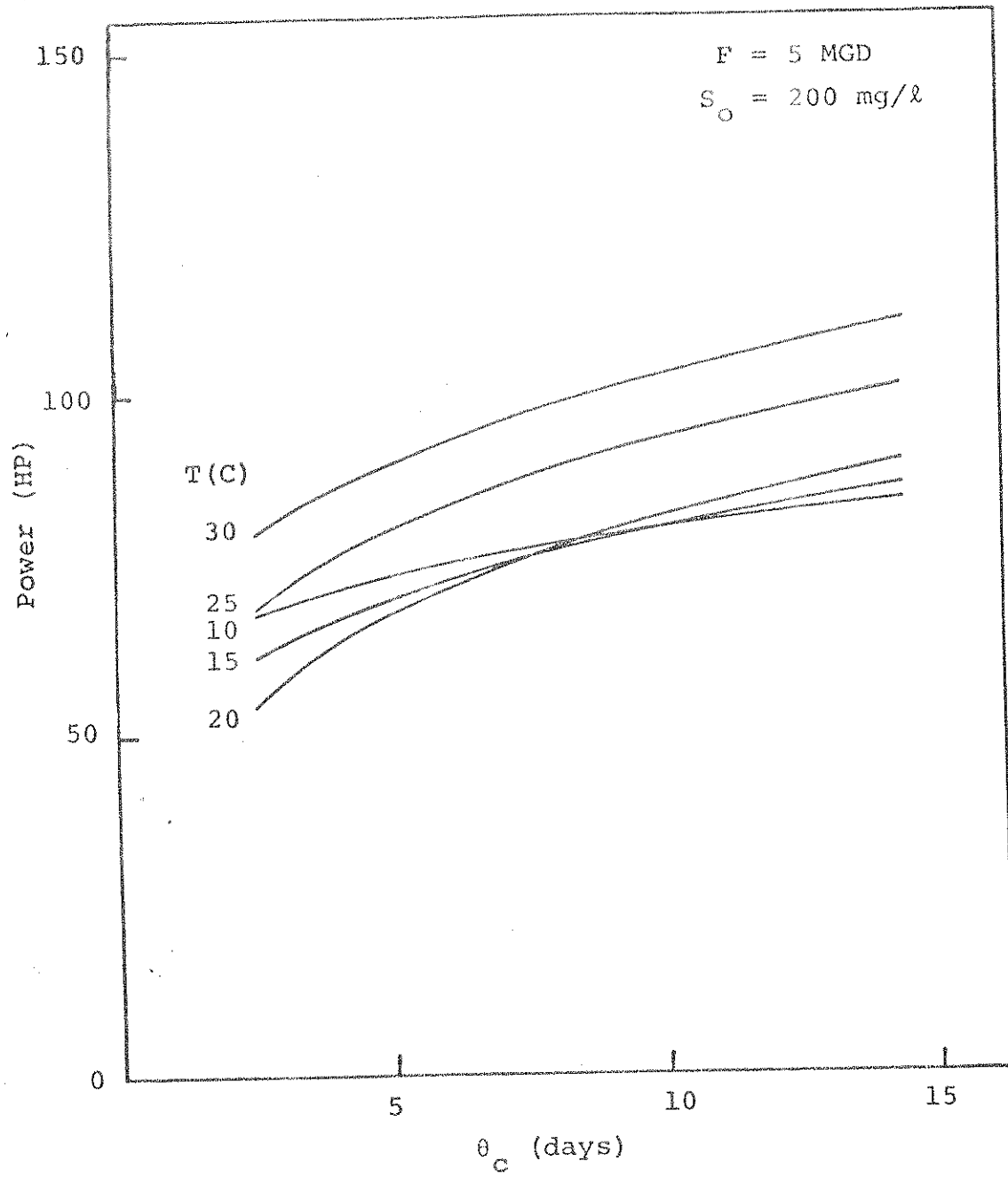


Figure 3.20 Effect of sludge age on power requirements for aeration.

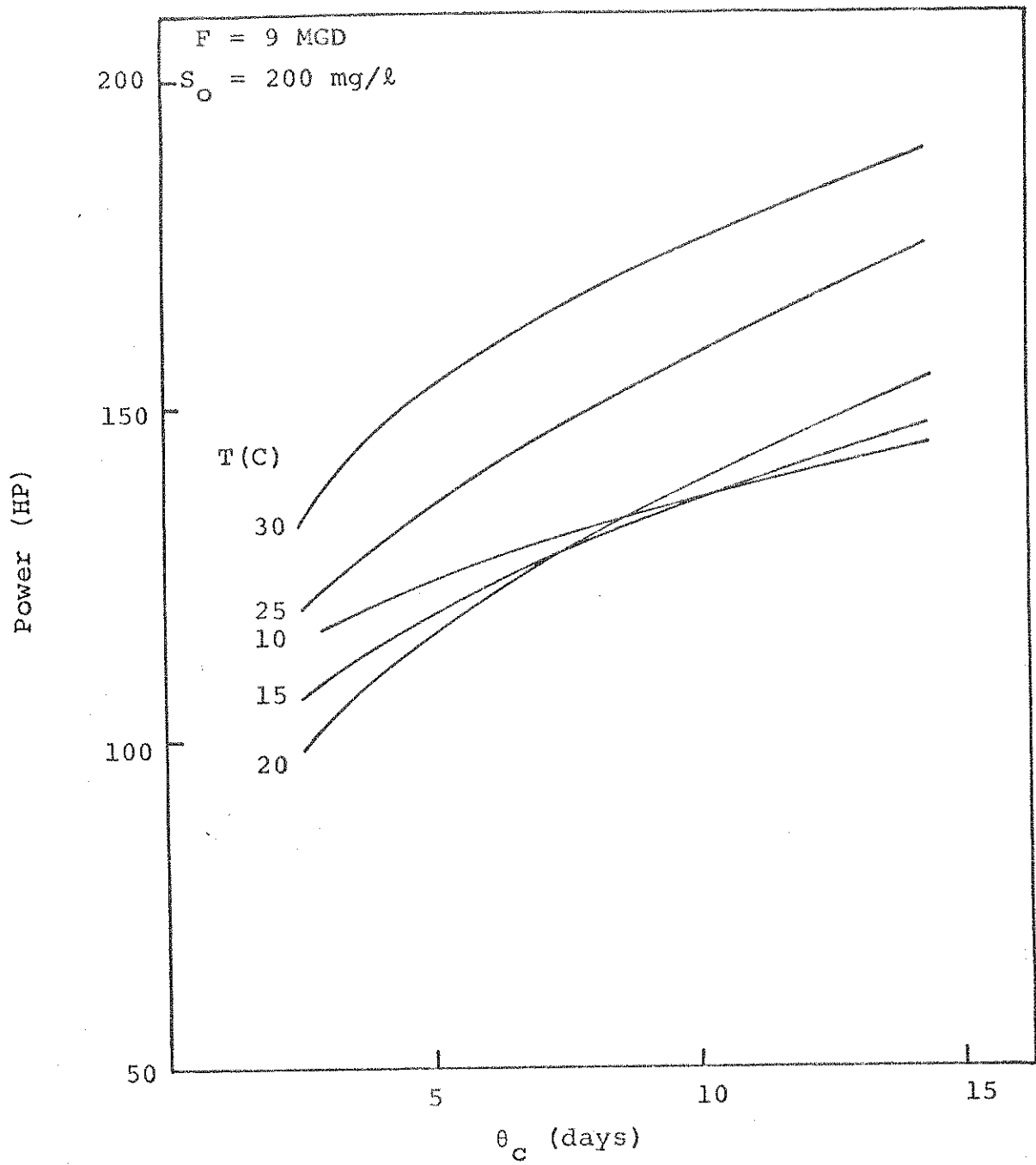


Figure 3.21 Effect of sludge age on power requirements for aeration.

for aeration increase as the temperature increases from 20 C. This is due to the increased oxygen demand of the bacteria and the decreased solubility of oxygen in water. The behavior of the power requirements for temperatures below 20 C is dependent upon the sludge age. As the sludge age increases, the power requirements increase due to the increased effect of cell decay.

### 3.3 Discussion of the Agnew Model

In the Agnew Model for clarification, the suspended solids in the effluent are taken to be inversely proportional to the concentration of cells in the aeration tank

$$X_{ec} = \left[ \frac{382 (F - F_w/A)^{0.12} \left( \frac{F S_o}{XV} \right)^{0.27}}{X^{0.35} \bar{t}} \right] \left( \frac{\mu_T}{\mu_{T_o}} \right) \quad (2.61)$$

Therefore, as the sludge age increases, thereby increasing the suspended solids in the aeration tank, the concentration of suspended solids in the effluent decreases. This condition is reflected by the results in Figures 3.22 and 3.23. Note that, although increasing the influent flow rate to 9 MGD increases  $X$ , the value of  $X_{ec}$  does not decrease due to the offsetting effect of the increase in  $F$ .

There would seem to be an anomaly in the Agnew model, and hence in the results of Figures 3.22 and 3.23, since one would expect the concentration of suspended solids in the effluent to increase with  $\theta_c$  due to the higher loading,  $X$ ,



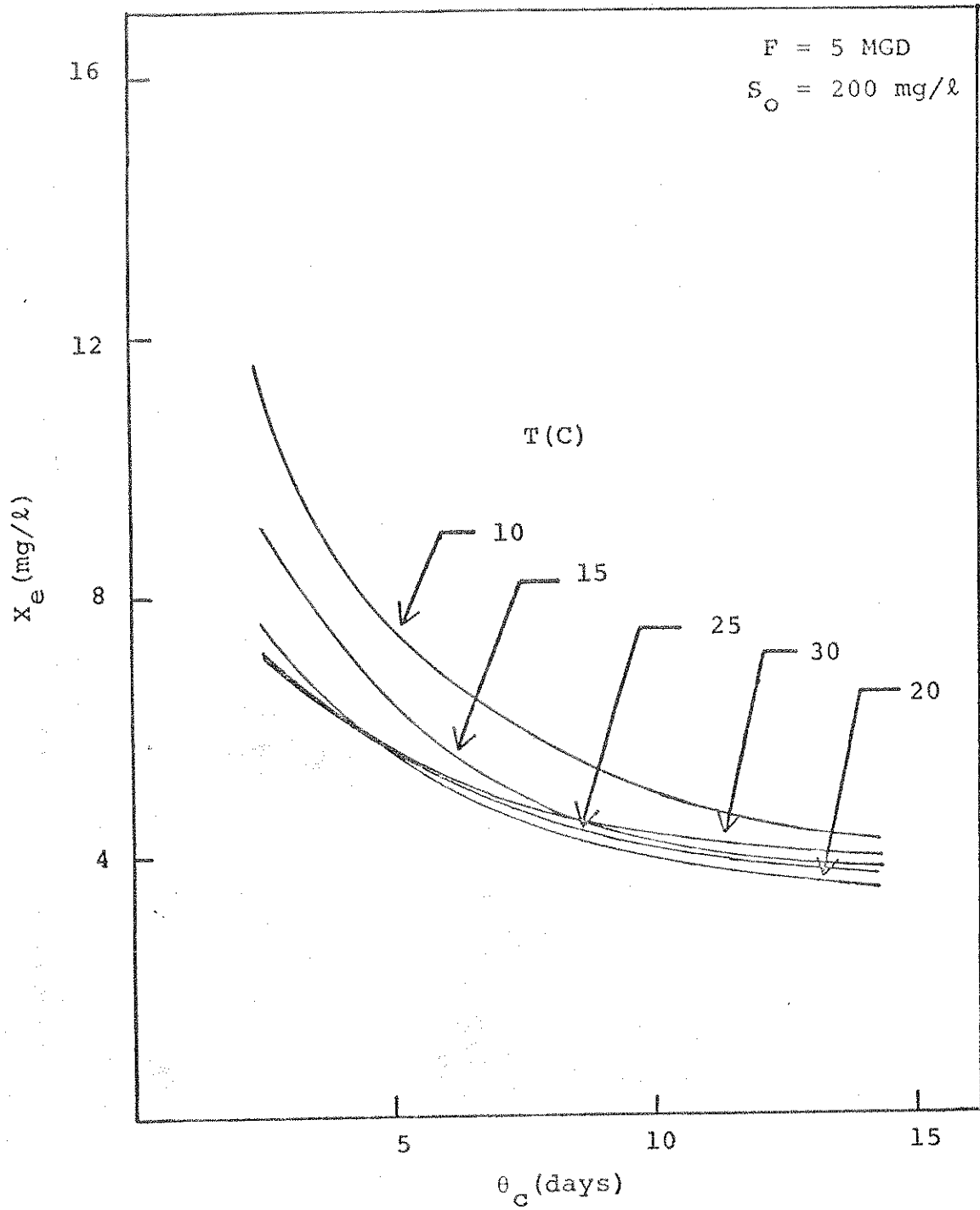


Figure 3.22 Suspended solids in the effluent for the Agnew settling model.

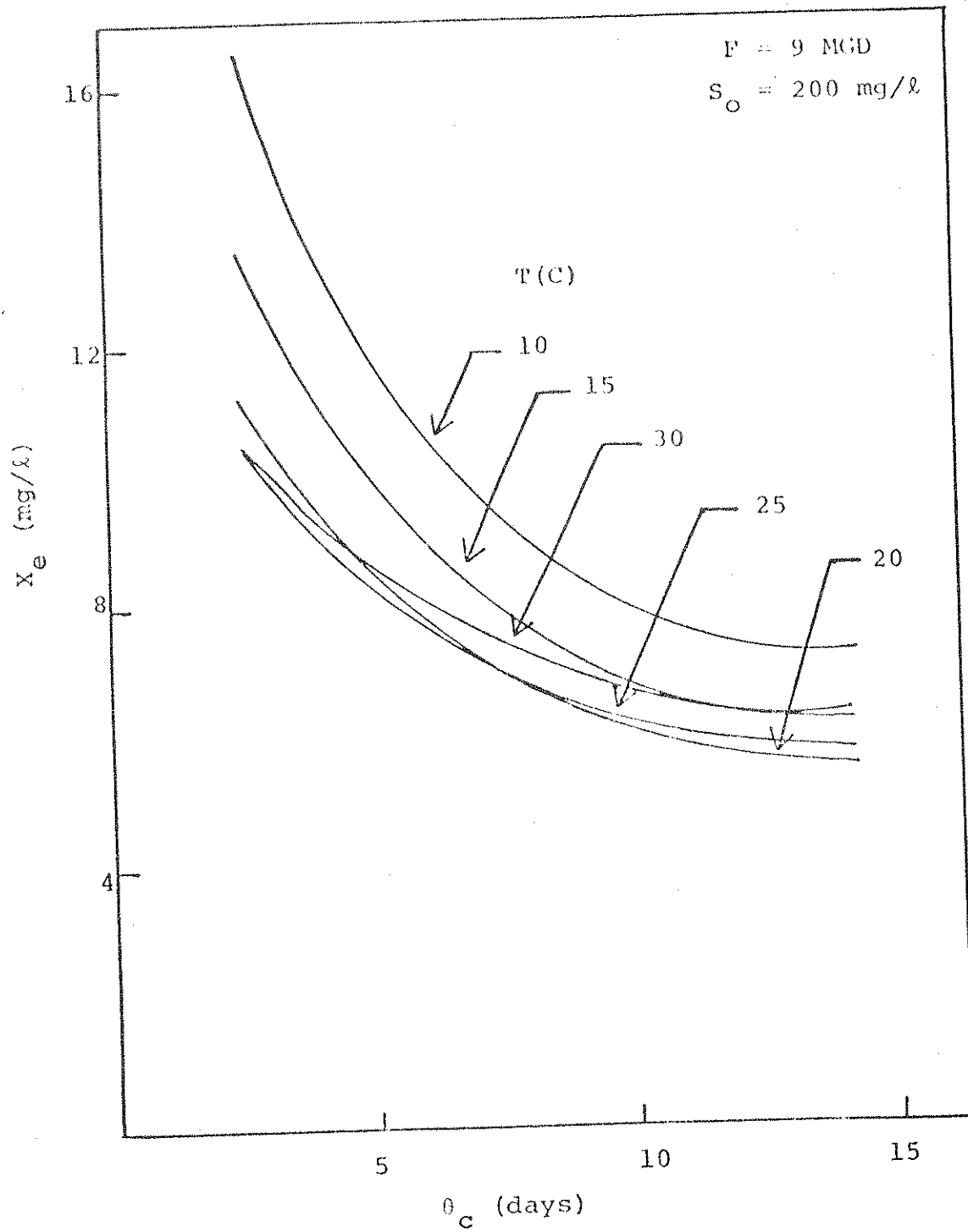


Figure 3.23 Suspended solids in the effluent for the Agnew settling model.

associated with large values of  $\theta_c$ . Hydraulic conditions for a given inflow are virtually constant, so there is uncertainty in accounting for the physical mechanisms which provide for the Agnew effect. It is important to note that other steady state models (50,51) predict similar trends, in which case there is no clear cut choice between the models of Agnew or Tarrer.

One effect of increasing temperature in the Agnew settling model is to increase the settling rate of solids due to the effect of temperature on the water viscosity. However, as discussed earlier, for fixed  $\theta_c$  the concentration of cells in the aeration tank,  $X$ , decreases with increasing temperatures greater than 20 C. These two effects are competing and provide for the observed minimum at temperatures between 20 and 25 C. The effect of temperature on  $X_{ec}$  indicates that, for both the Agnew and Tarrer models, temperatures below 20 C result in less than optimal operation.

Figures 3.24 and 3.25 portray the effect of sludge age on total effluent quality. Since the effluent soluble substrate concentration is independent of influent conditions and depends only on sludge age, Figure 3.3 also provides the effect of sludge age on soluble substrate concentration for the present model. Although the total effluent quality increases with increasing sludge age, the value of  $\theta_c$  may not be increased without limit. Beyond a certain critical value of  $\theta_c$  the solids handling capacity of the settler will be

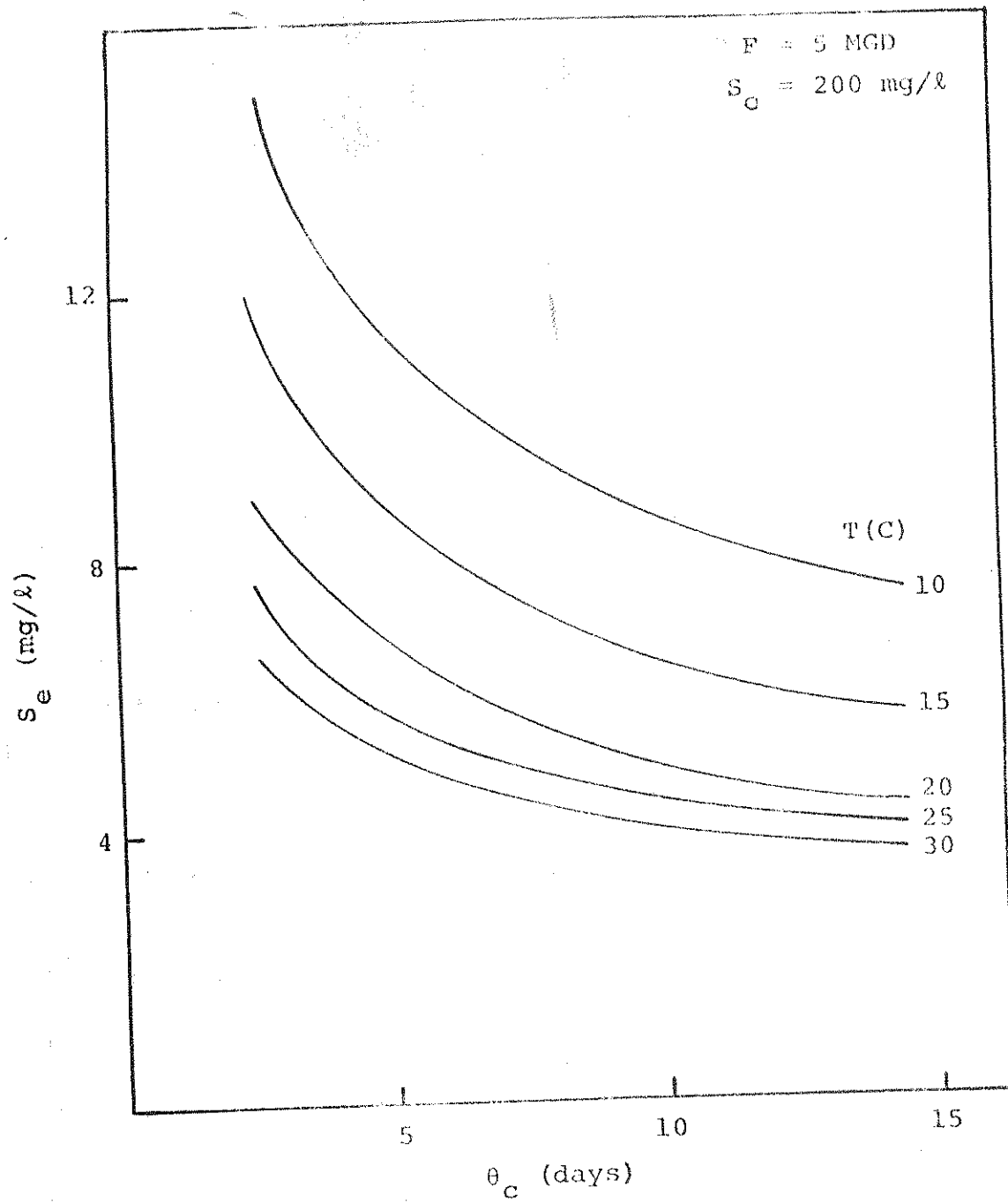


Figure 3.24 Effect of sludge age on total effluent quality for the Agnew settling model.

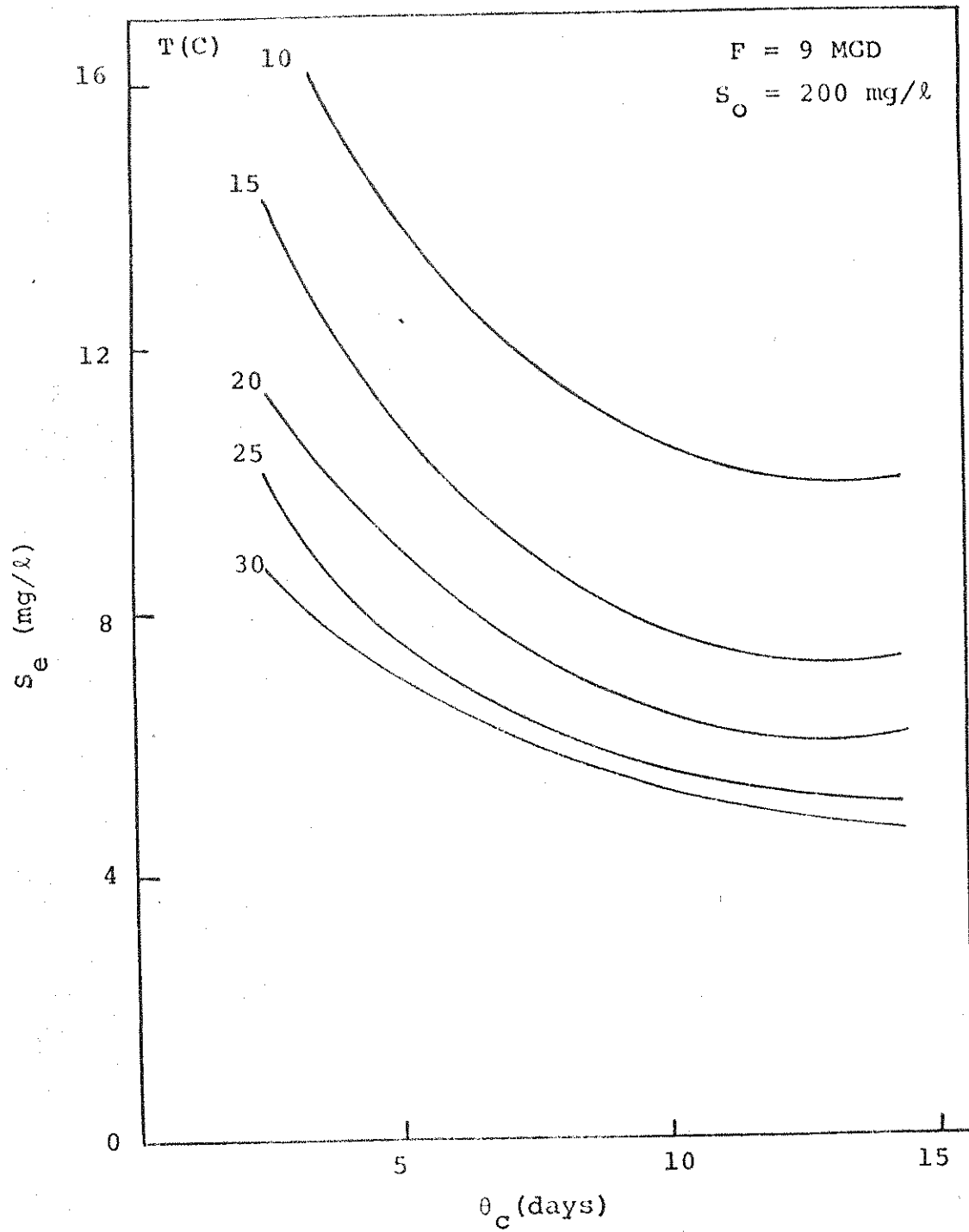


Figure 3.25 Effect of sludge age on total effluent quality for the Agnew settling model.

exceeded. For this case, the  $X_{et}$  term (suspended solids loss due to thickener failure) in equation (2.55) increases rapidly from an initial value of zero. Moreover, as West (79) has shown, sludge ages in excess of about 14 days may result in pin-floc, which is difficult to settle and reduces the effluent quality. Consequently, an upper limit must be set on the sludge age. Comparing Figures 3.24 and 3.25 with Figures 3.4 and 3.5, the effect of the different clarification models on the total effluent quality becomes evident. The increasing suspended solids in the effluent predicted by the Tarrer model results in a total effluent quality which clearly deteriorates at extended sludge ages. This result is in contrast to that predicted by the Agnew model, and it is evident that the total effluent quality is highly dependent upon the ability of the settler to clarify the waste.

The effect of temperature on total effluent quality is shown in Figures 3.26 and 3.27. The total effluent quality improves with increasing temperature, which is equivalent to the trends shown in Figure 3.6 for the Tarrer model.

The gross rate of sludge production predicted by the Agnew model is the same as that for the Tarrer model, as shown in Figures 3.8 and 3.9. This is because gross sludge production is independent of the settling model and depends only on influent conditions and sludge age. However, the amount of solids lost over the final settler does depend

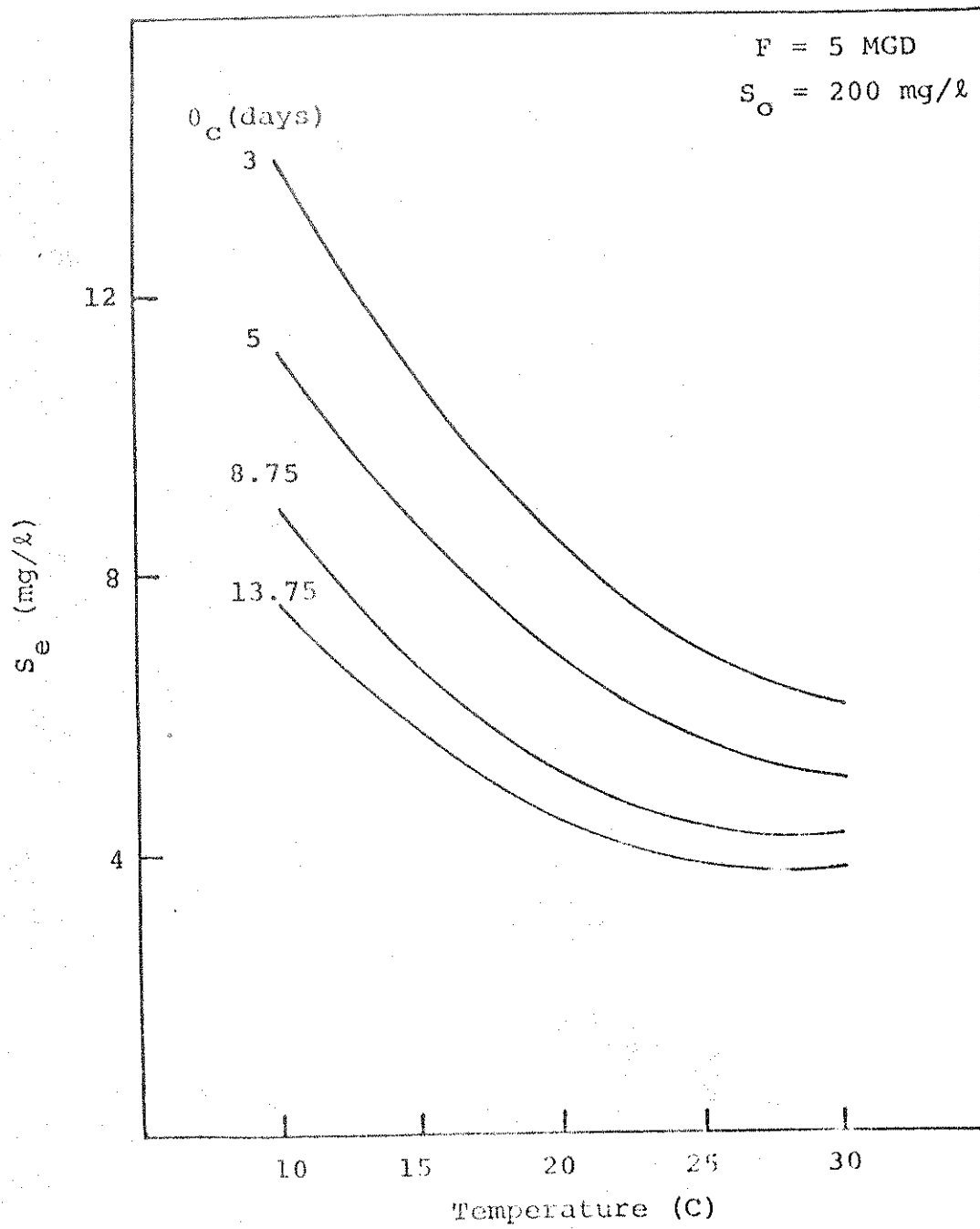


Figure 3.26 Effect of temperature on total effluent quality for the Agnew settling model.

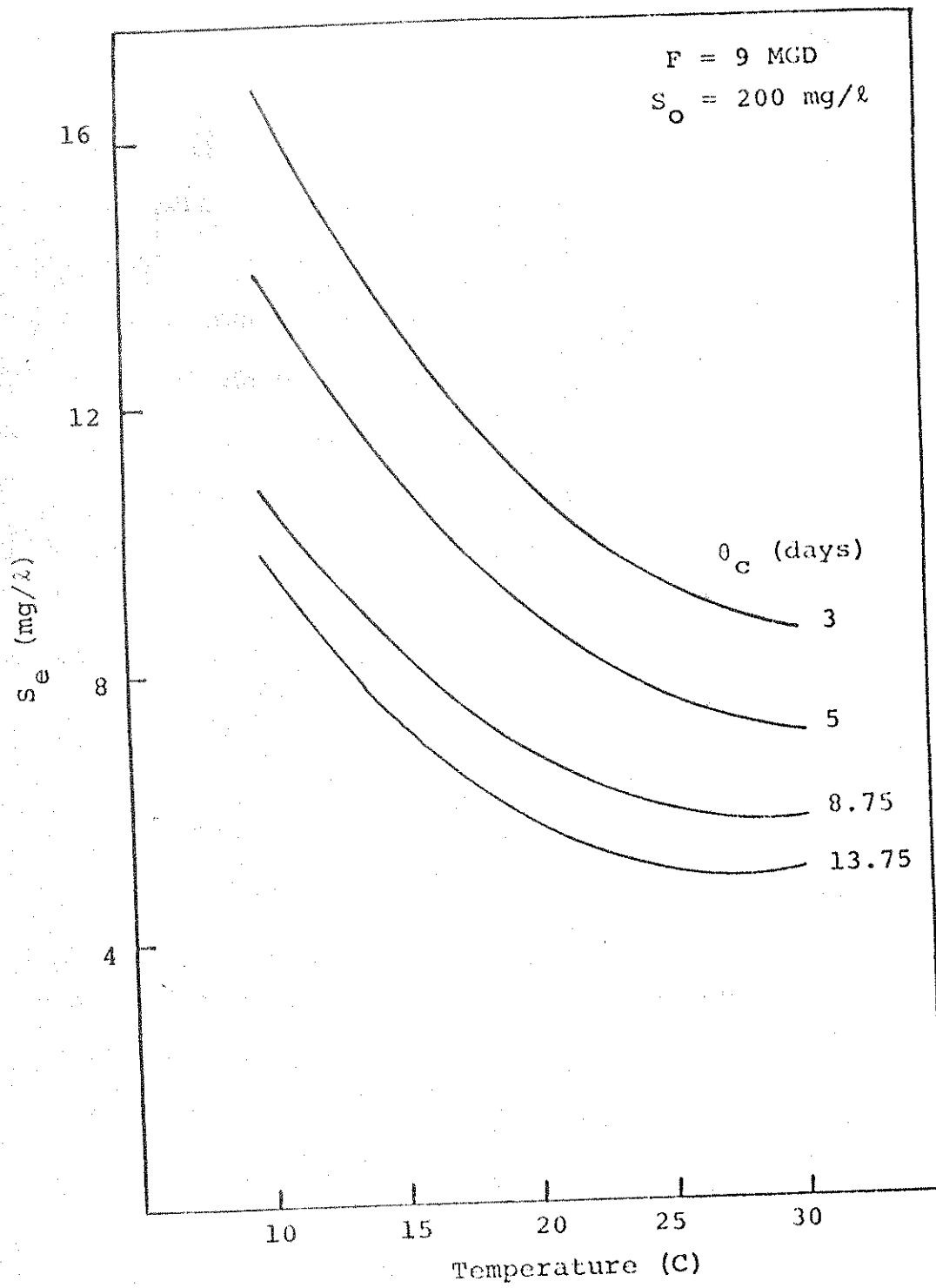


Figure 3.27 Effect of temperature on total effluent quality for the Agnew settling model.



on the settling model, and the results obtained for the Agnew model are shown in Figures 3.28 and 3.29. The net mass wastage rate for the Agnew model will differ from that obtained for the Tarrer model, and the results are shown in Figures 3.30 and 3.31. The effect of the different clarification model is to have the highest suspended solids loss over the final settler at the low sludge age which is just the opposite of the Tarrer model, which has the highest suspended solids loss at extended sludge ages. The effect then, of the Agnew settling model is more pronounced at low values of  $\theta_c$ .

The effect of temperature on the net mass wastage rate is shown in Figures 3.32 and 3.33. The mass wastage rate decreases rapidly as the temperature increases above 20 C. For temperatures less than 20 C, the effect of cell decay becomes more pronounced at large values of  $\theta_c$ , as discussed earlier.

Since aeration requirements are independent of the settling characteristics and depend only on sludge age, the power requirements for aeration predicted by the Agnew model are the same as those predicted by the Tarrer model.

In summary, the Agnew model for clarification predicts a decreasing concentration of effluent suspended solids with increasing  $\theta_c$ , which results in increasing effluent quality for longer sludge ages. The increased loss of suspended solids for decreasing  $\theta_c$  results in a net mass wastage rate

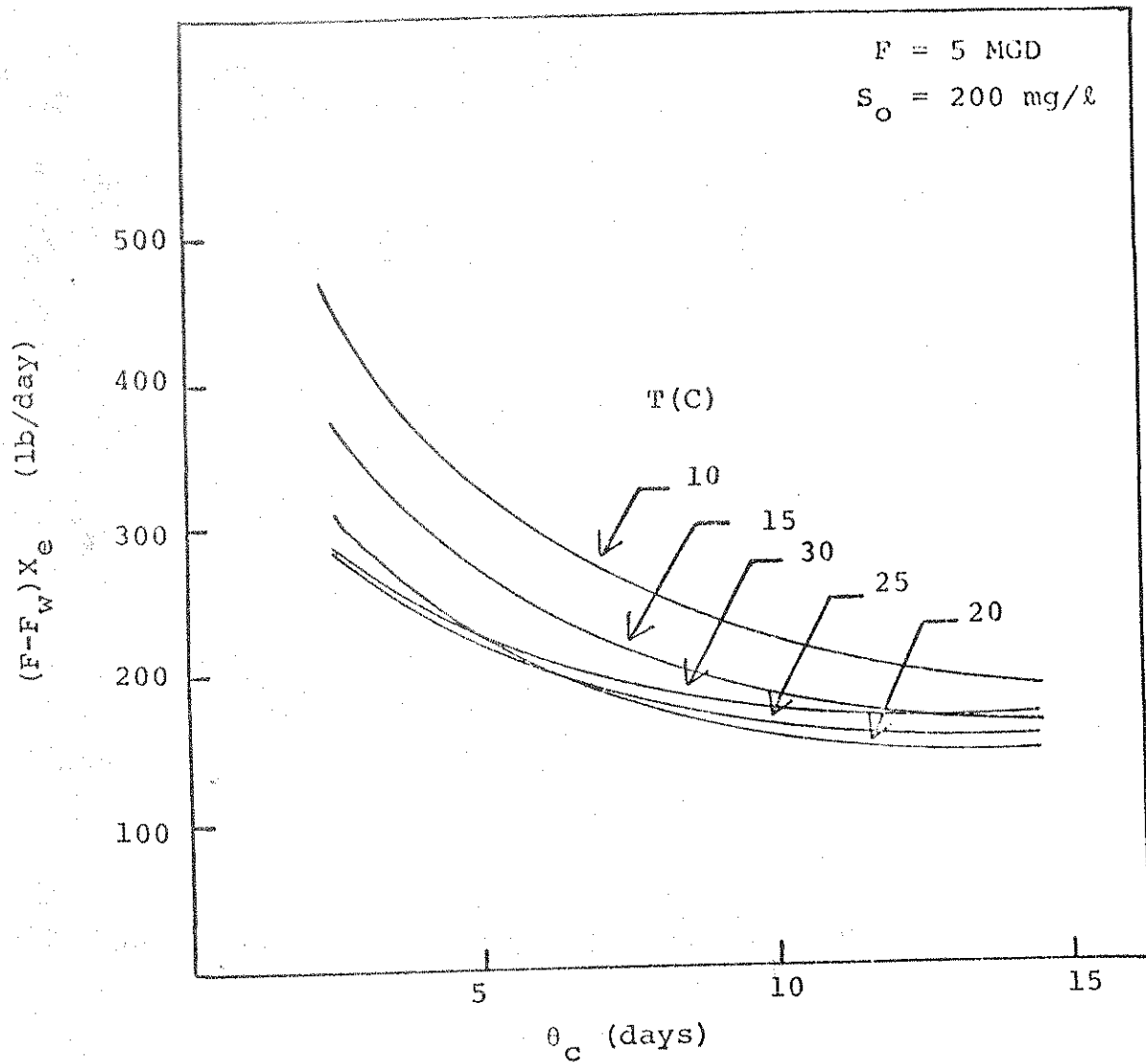


Figure 3.28 Effect of sludge age on rate of loss of solids over final settler for the Agnew settling model.

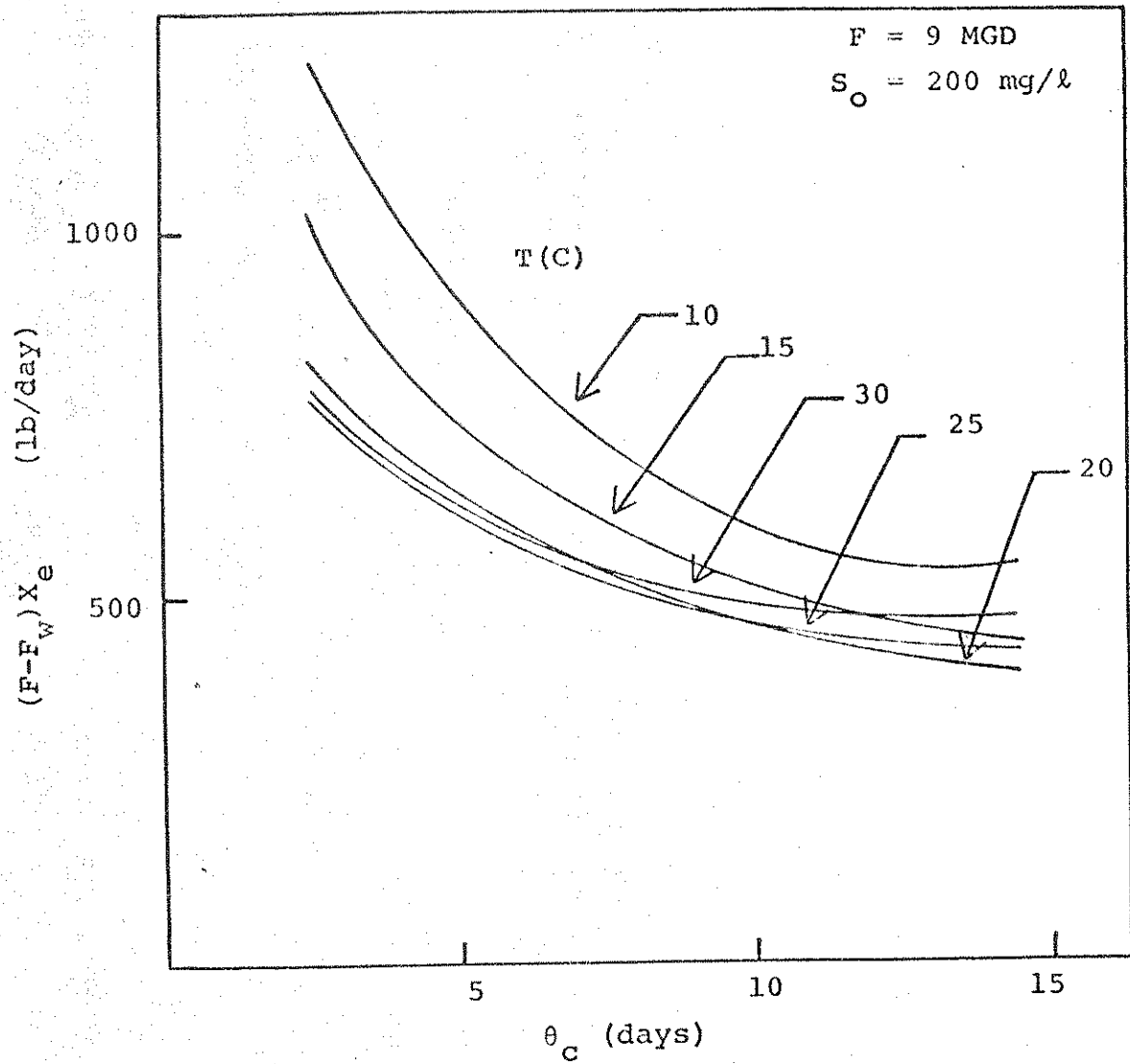


Figure 3.29 Effect of sludge age on rate of loss of solids over final settler for the Agnew settling model.

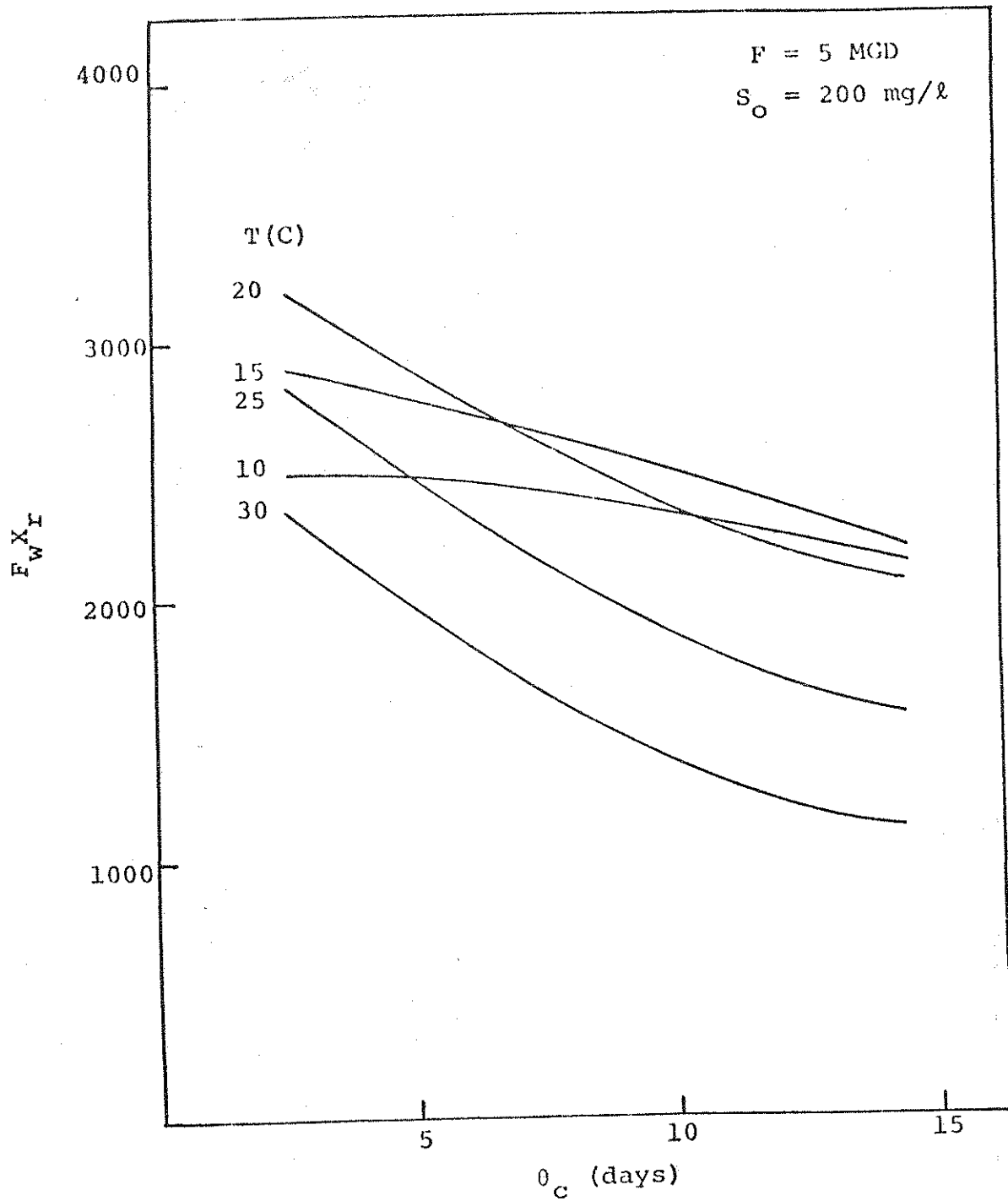


Figure 3.30 Effect of sludge age on net mass wastage rate for the Agnew settling model.

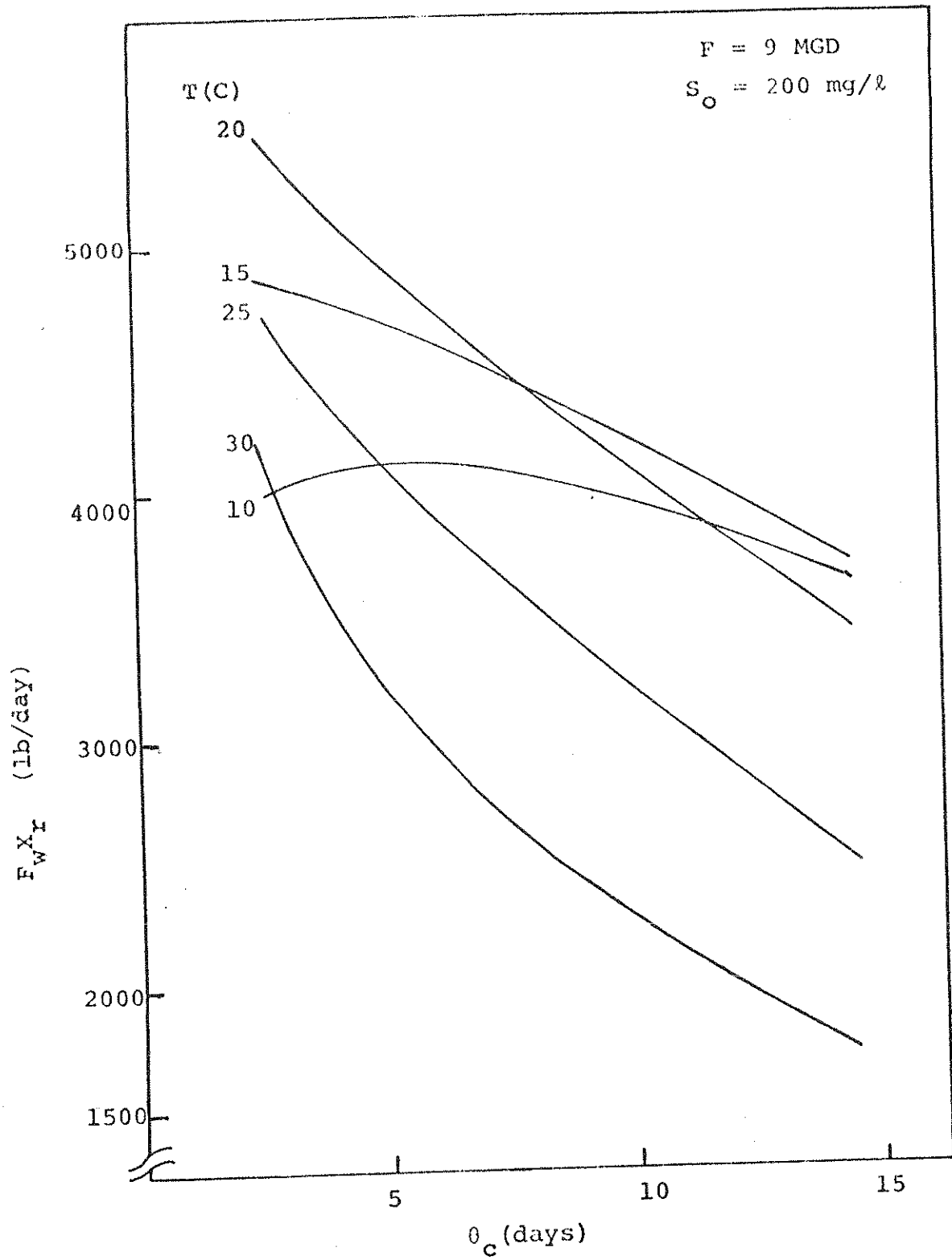


Figure 3.31 Effect of sludge age on net mass wastage rate for the Agnew settling model.

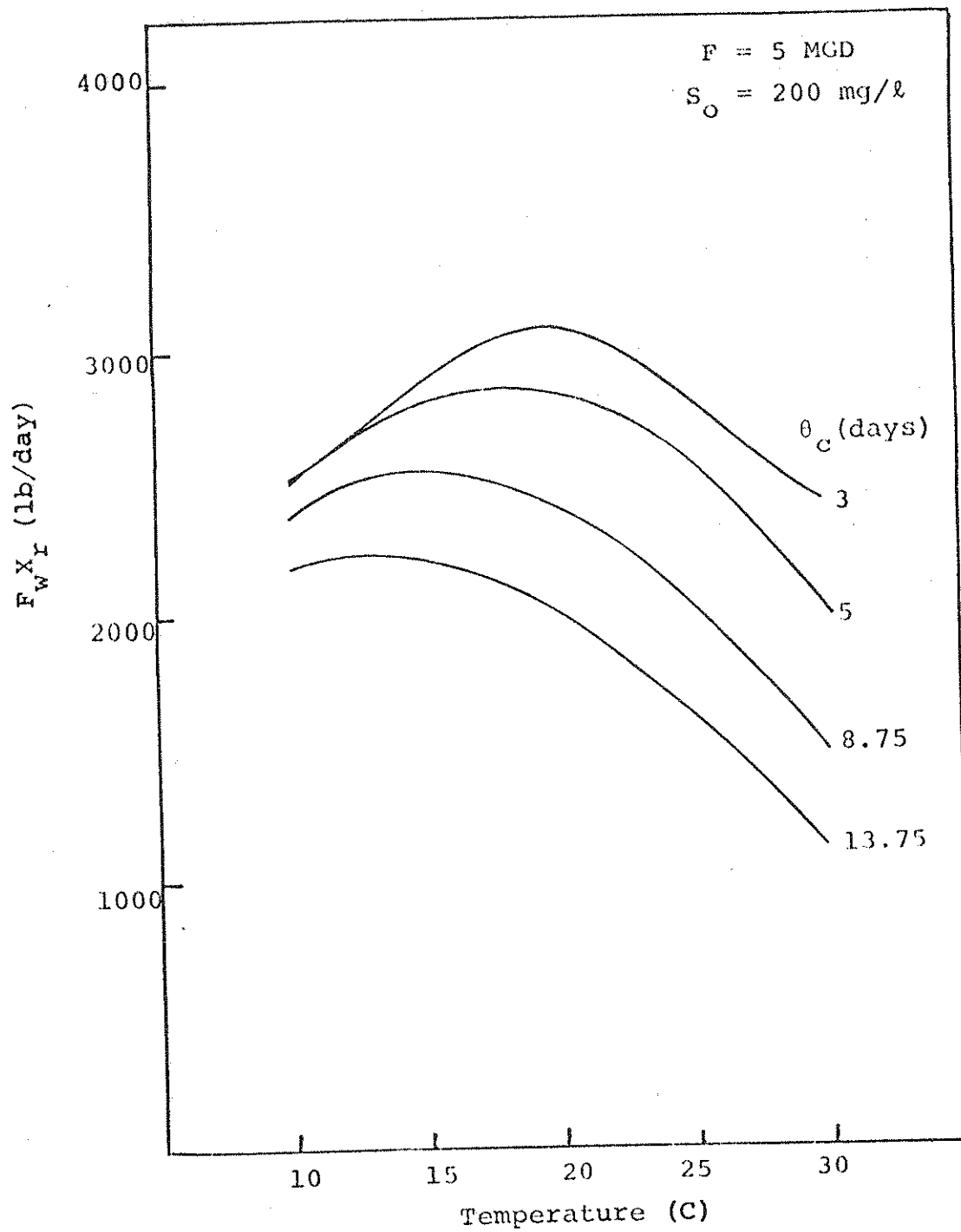


Figure 3.32 Effect of temperature on net mass wastage rate for the Agnew settling model.

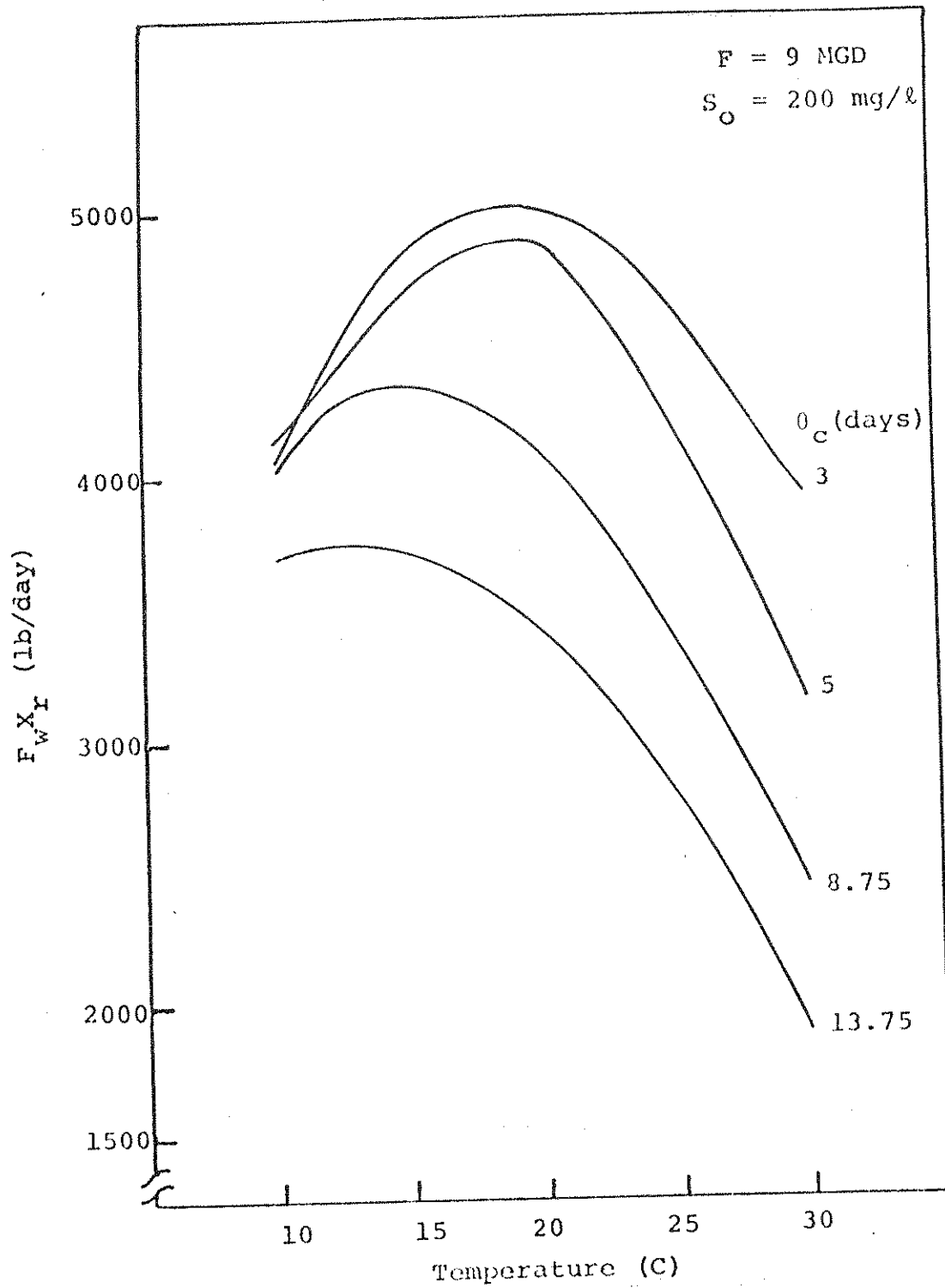


Figure 3.33 Effect of temperature on net mass wastage rate for the Agnew settling model.

at low sludge ages that is less than that predicted by the Tarrer model. The power requirements for aeration are the same as those predicted for the Tarrer model, since the oxygen demand and oxygen transfer are independent of the settling characteristics.

### 3.4 Summary

Temperature control of secondary wastewater treatment facilities can be beneficial if a proper temperature can be maintained. Effluent quality is improved for any temperature increase in the range from 10 to 30 C. The major difficulty lies in obtaining a proper balance between the amount of sludge produced and the oxygen requirements of the system. Although the amount of sludge produced is maximized at 20 C, this production may be significantly reduced for any increase in temperature above 20 C. Since sludge disposal constitutes a major operating cost of the system, reduced production is highly desirable. However, at elevated temperatures, the power required to maintain aerobic conditions in the system is increased. Hence some balance between the sludge produced and power requirements of the system must be established. Tables 3.1 and 3.2 illustrate the effect of temperature changes from operation at 20 C. A minus sign indicates a decrease, in either power requirements or sludge production. The effects of temperature on net and gross sludge production are included, to illustrate the effect of the settling model on sludge



Table 3.1 Percent changes in sludge production and power requirements relative to operation at 20 C (F=5 MGD).

<u>Temperature</u>	<u>Sludge Production</u>			<u>Power</u>
	% change Gross	% change, Net Tarrer (48)	% change, Net Agnew (52)	% change
$\theta_c = 13.75$ days				
10	+4.49	+3.57	+4.76	-5.6
15	+6.74	+5.95	+5.95	-5.6
20	0	0	0	0
25	-22.47	-21.42	-25.0	+11.0
30	-42.69	-41.66	-46.42	+22.74
$\theta_c = 8.75$ days				
10	-3.77	-3.84	-5.94	-1.25
15	+1.88	+0.96	0	-3.75
20	0	0	0	0
25	-18.86	-20.19	-20.79	+13.75
30	-39.62	-38.46	-42.57	+25.0
$\theta_c = 5.00$ days				
10	-10.32	-10.56	-15.38	+7.35
15	-2.38	-3.25	-5.13	+1.47
20	0	0	0	0
25	-18.86	-13.82	-15.38	+17.64
30	-31.74	-29.26	-32.48	+32.35

Table 3.1 (cont.)

<u>Temperature</u>	<u>Sludge Production</u>		<u>Power</u>	
	% change Gross	% change, Net Tarrer (48)	% change, Agnew (52)	% change
$\theta_c = 3.00$ days				
10	-15.94	-14.7	-22.22	+17.24
15	-5.79	-6.61	-8.73	+10.34
20	0	0	0	0
25	-13.04	-9.55	-13.49	+22.41
30	-26.09	-17.64	-27.77	+41.38

Table 3.2 Percent changes in sludge production and power requirements relative to operation at 20 C (F=9 MGD).

<u>Temperature</u>	<u>Sludge Production</u>				<u>Power</u>
	% change Gross	% change, Net Tarrer (48)	% change, Net Agnew (52)	% change	
$\theta_c = 13.75$ days					
10	+2.43	-8.45	-1.39	-7.04	
15	+4.27	+0.70	+4.16	-4.6	
20	0	0	0	0	
25	-25.0	-21.83	-24.3	+13.16	
30	-45.12	-38.73	-48.61	+23.02	
$\theta_c = 8.75$ days					
10	-2.59	-9.09	-8.04	0	
15	+0.52	-3.41	0	+2.4	
20	0	0	0	0	
25	-19.17	-21.59	-22.41	+18.30	
30	-38.86	-39.77	-43.86	+36.8	
$\theta_c = 5.00$ days					
10	-10.61	-12.38	-20.19	+9.48	
15	-3.53	-5.71	-7.69	+2.58	
20	0	0	0	0	
25	-15.92	-13.91	-21.75	+16.37	
30	-31.42	-29.52	-37.5	+32.75	

Table 3.2 (cont.)

<u>Temperature</u>	<u>Sludge Production</u>			<u>Power</u>
	% change Gross	% change, Net Tarrer (48)	% change, Net Agnew (52)	% change
$\theta_c = 3.00$ days				
10	-15.04	-14.16	-25.11	+13.59
15	-5.69	-7.29	-10.23	+5.8
20	0	0	0	0
25	-14.63	-10.72	-13.49	+19.41
30	-26.01	-22.32	-29.30	+34.95

disposal. For extended sludge age the sludge production can be reduced by more than 40% while the power required increases by about 20% with a temperature increase from 20 to 30 C. These figures are directly related to the costs of operation.

Since the effluent quality improves with increasing temperature, any temperature increase provides for improved treatment of the waste. However, it appears that a temperature in the range between 23 and 27 C and a sludge age between approximately 8 and 14 days may provide the best combination of effluent quality, mass wastage rate and power requirements. The longer sludge age of 14 days for the Tarrer model may only be possible if the total effluent quality does not exceed limitations imposed by the Water Quality Act of 1972.

This study has been concerned with simulation of an actual wastewater treatment facility, and it models the general trends associated with temperature variations. The temperature variation of the kinetic parameters  $\mu_m$ ,  $b$  and  $Y_g$  is well documented, although there exists some uncertainty concerning the precise numerical values which are appropriate for a given system. In contrast, because of the uncertainties in the temperature variation, the kinetic parameters  $K_s$  and  $\gamma$  were taken as constants. The only dependent variable which is directly influenced by  $K_s$  and  $\gamma$  is the effluent soluble substrate concentration. If  $K_s$

increased with increasing temperature, it would tend to offset the effect of increasing  $\mu_m$ , thereby increasing the effluent soluble substrate concentration. In turn a decrease in  $K_s$  would decrease the effluent soluble substrate concentration. Although the effect of temperature on  $\gamma$  could well be analogous to its effect on  $\mu_m$  and  $b$ ; that is, the effect could be represented by an Arrhenius expression, such an expression was not used due to lack of any information on the temperature dependence of  $\gamma$ . However, if  $\gamma$  did increase with temperature, it would tend to increase the effluent soluble substrate concentration.

Unfortunately, the effect of temperature on sludge settling rates has not been well documented. There is some feeling that the settling rate increases with increasing temperature and that this is due, at least in part, to temperature effects on viscosity. However, there is presently no substantive information on the matter. If the settling rate were independent of viscosity, it would only depend on the cell concentration in the aeration tank, which decreases with increasing temperature. This is unfortunate because there is presently considerable uncertainty concerning the effect of cell concentration in the aeration tank on clarification conditions in the settler. In one model the clarification ability of the settler is directly proportional to the cell concentration in the aeration tank, while other models predict an inverse

proportionality. There is little to choose between the two. However, the inclusion of viscosity effects on the settling rate was felt to be appropriate, at least until further information becomes available.

The effects of temperature on thickening are not large and do not have much influence on the results of this study.

In addition to depending on the kinematic parameters mentioned earlier ( $\mu_m$ ,  $b$  and  $Y_g$ ), the oxygen demand of the bacteria also depends on  $\beta$ , the oxygen equivalent of cells formed. The quantity  $\beta$  is also likely to be temperature dependent, but there is little information available (28). If  $\beta$  increases with increasing temperature, it will decrease the oxygen demand of the cells; while if it decreases, the oxygen demand will increase.

Overall, it is felt that the present model provides a reasonable description of the effect of temperature on a biological wastewater treatment facility. Verification of the model depends on laboratory tests and/or full-scale operation at controlled temperatures, with measurement of the output parameters such as total effluent quality, mass wastage rate and power requirements.

In regards to the ultimate possibility of using waste heat for maintaining biological wastewater treatment facilities at an elevated temperature would seem best for an integrated power plant - wastewater treatment facility. This would require siting of the power plant and wastewater

treatment facilities adjacent to each other in order to minimize pumping costs and transmission energy losses. For this case there are definite benefits to the wastewater treatment facility due to improved operating characteristics. In particular, the effluent quality is improved and the production of sludge is reduced. These can be used to offset the increased power requirements at elevated temperatures. Although the use of waste heat by already existing plants would depend on the distance the power plant would have to be pumped and the cost of alterations, it is unlikely that the economics would justify the use of waste heat in this case.



## CHAPTER 4 CONCLUSIONS

The salient features of the mathematical model for the temperature controlled biological wastewater treatment plant are as follows.

1. Temperature effects can be separated into two categories which include the effect of temperature on the bio-system and the effect of temperature on physical operation.
2. Temperature affects the biosystem through the kinetic parameters  $\mu_m$ ,  $b$  and  $Y_g$ . The kinetic parameters affect, in turn, the effluent soluble substrate concentration, the gross mass wastage rate and the oxygen demand of the culture.
3. Temperature affects the physical operation of the system through the oxygen solubility and the viscosity of water. Any change in solubility affects the oxygen transfer capabilities of the spargers, whereas any change in viscosity affects the settling rate of the suspended solids and thus the rate of loss of suspended solids over the final settler.
4. Increasing temperature improves the total effluent quality.
5. Increasing temperature increases the oxygen demand of the system, which increases the power requirements for aeration.

6. The mass wastage rate decreases as the temperature increases above 20C.

7. A balance can be made between the increased power demand and decreased mass wastage rate to show that temperature control can be beneficial. In particular a temperature of 25C appears to provide a suitable compromise between the mass wastage and power requirements.



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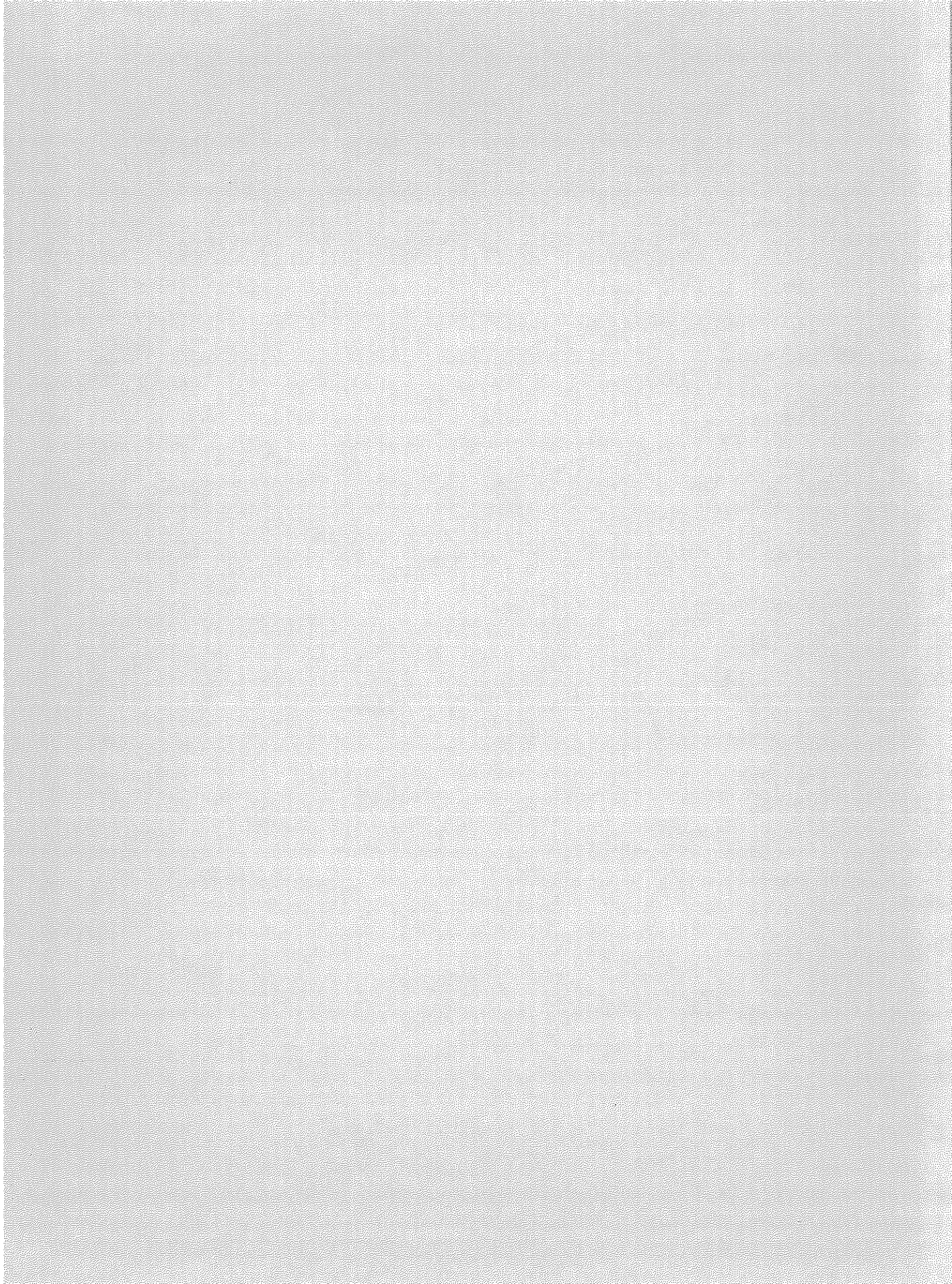


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